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MOUNTAINS

THEIR ORIGIN, GROWTH, AND DECAY

THE MATTERHORN, A MOUNTAIN WITHOUT "ROOTS."
Photo, Rev. L. J. Causton.

MOUNTAINS

THEIR ORIGIN, GROWTH AND DECAY

BY

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TWENTY-FIVE PARK PLACE

TO HIS

OLD FRIENDS AND COLLEAGUES

ON THE

COUNCIL OF THE ROYAL SCOTTISH GEOGRAPHICAL SOCIETY

THIS VOLUME IS RESPECTFULLY AND GRATEFULLY

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PREFACE

THIS work deals almost exclusively with the borderland of Geology and Geography. The main subject discussed—the architecture and origin of mountains —might well require several volumes to do it justice. Here all that has been attempted is such a comprehensive sketch as may be helpful to readers not specially versed in Geology, who desire a fuller statement of the subject than is usually presented in geographical text-books. Although within recent years the complicated structures characteristic of mountains of uplift have been more clearly realised than heretofore, it must be admitted that much still remains obscure. This part of my theme, therefore, might have been passed over with a few general remarks on the difficulties of unravelling and explaining the puzzling phenomena of mountain architecture. But I thought it would be more instructive to give some particular account of the structures in question, and to indicate the interpretations advanced by geologists who have made these a special study. I have also ventured to discuss the more notable theories which have from time to time been entertained as to the genesis of mountain-uplifts, and to place before the reader the present position of that interesting question.

The many technical terms employed by specialists have been as far as possible avoided, but it is not always easy or even desirable to do without them. Those introduced, however, are explained either in the text or in the accompanying glossary. For convenience of reference, indeed, the explanations given in the text are usually repeated, with or without additional detail, in the glossary.

In the preparation of this volume free use has been made of an essay on "Mountain Structure and Its Origin," contributed to the *International Monthly* (1901), and of papers on the "Architecture and Origin of the Alps," and the "Deeps of the Pacific Ocean," which lately appeared in the *Scottish Geographical Magazine* (1911, 1912).

My cordial thanks are due to Miss M. Newbigin, D.Sc., Rev. L. J. Causton, Dr Carnegie Dickson, and J. W. Reoch, Esq., for kindly supplying me with photographs which are here reproduced. I am also indebted to Messrs Holt & Co., New York, for clichés of several illustrations from Professor Salisbury's admirable *Physiography*. The sources of these and other illustrations appearing either in the text or as page-plates, are all duly indicated; and the reader will note how largely I have availed myself of the beautiful and instructive photographs issued by H.M. Geological Survey.

JAMES GEIKIE.

SLIGACHAN, ISLE OF SKYE,
23rd August 1913.

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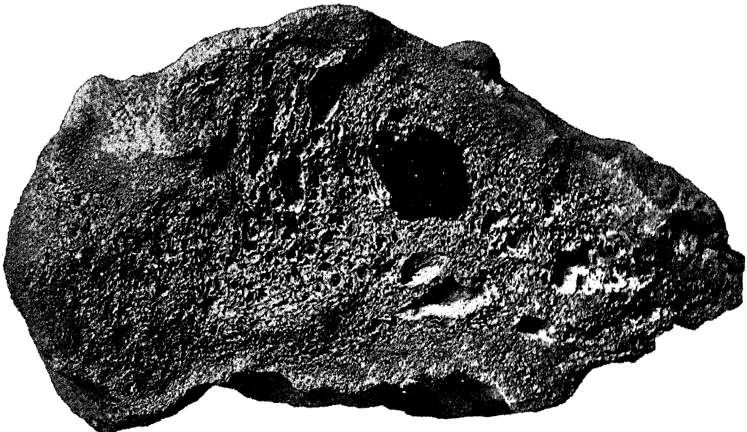
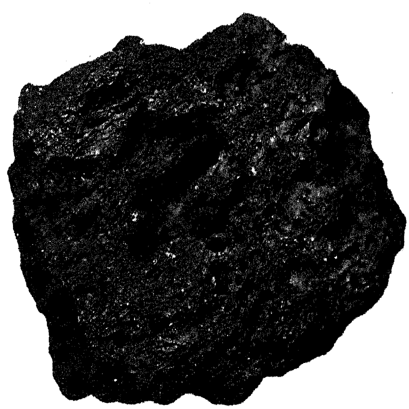


1. SCORIA OR CINDER (GRAND CANARY). About half natural size.



2. SCORIA OR CINDER (TENERIFFE). About natural size.

MOUNTAINS

CHAPTER I

ORIGINAL OR TECTONIC MOUNTAINS

Classification of Mountains. Mountains of Accumulation: Volcanic Forms—Debris Cones, Lava Cones, Cones of Viscous Lava, Cones of Liquid Lava, Composite Cones, Truncated Cones, Cone-in-cone Structure.

MOUNTAINS, valleys, plateaus, and plains—what more comprehensive classification of land-forms could be devised? It is not only comprehensive, but must seem natural to anyone who has even an elementary acquaintance with physical geography. And yet when we come to study the various forms assumed by the land, we are not infrequently puzzled to discriminate between plateaus and mountains, and even between valleys and plains. Thus one and the same elevated tract is sometimes described by topographers as a plateau, sometimes as a chain of mountains; while now and again plains, valleys, and other depressions are similarly confounded the one with the other. The definitions of these geographical terms given in the text-books are often precise and truly descriptive of certain types; but the very fact that topographers are not always

manifold modifications, but these are due to secondary causes, obvious or obscure as the case may be. They are, as it were, accidental and not essential characters. A geological classification of mountains, therefore, must in many respects differ from a topographical arrangement.

Sentimentalists have sometimes expressed the fear that a study of the structure or anatomy of mountains may diminish one's appreciation of scenery. But surely it ought rather to lend an additional interest to our contemplation of Nature. A botanist is not less able to realise the beauty of flowers because he fully understands their structure and life-history; neither does an anatomist's knowledge of the human frame prevent his lively recognition of loveliness in woman. If no special acquaintance with geology be required to open the eyes of artists and poets to the charms of scenery, it is hard to conceive why some comprehension of the origin of that scenery — some intelligent perception of its design—should lessen their delight in its beauty. Even if well versed in the stony science, they need not fail to be impressed by the awe-inspiring majesty and grandeur of soaring peaks and stupendous depths, the lights and shades and changing colours of heights and hollows. It is true that the geologist is not so free as others to let his fancy roam, and to indulge in vague dreams as to the birth of mountains. He may talk of a tumbled sea of mountains, but that is only a figure of speech: he does not really believe with the poets that some great convulsion has tossed

the crust into heaving billows, that beetling cliffs and serrated ranges are the crests of mighty earth-waves suddenly arrested in their mad career. He knows, indeed, that deformations of the crust have taken place again and again, but the rugged mountain-features just referred to are rarely, or never, the result of violent paroxysmal movement. The most considerable chains and ranges have been formed in many different ways—some no doubt being indicative of former crustal disturbance, others of volcanic action, while a large number owe their existence to the operation of superficial agents of change, which at first sight one would hardly think were capable of producing such results. But even in the case of lofty mountains of upheaval the existing configuration cannot be original. All, even the youngest, have undergone wholesale modification since their appearance. The features which most impress artists and poets are of secondary origin.

It is not only the greater elevations of our globe, however, but even lowly hills, that we are about to study. The dictionaries tell us that a mountain is "an elevation of the land of considerable dimensions, rising more or less abruptly above the surrounding or adjacent country," while a hill is "a natural eminence not so high as a mountain." The vagueness of these definitions shows us that the terms, as everyone recognises, are only relative, "elevations of the same height being called hills in one locality and mountains in another." As we have no word sufficiently comprehensive to include eminences of

every height and size, we must fall back on the term mountain, giving to it a wider signification than it usually carries. To the topographer height and dimension are of prime importance in his description of salient land-forms, and he has an abundant vocabulary at his command, such as mound, hummock, knoll, monticle, hillock, hill, ridge, down, fell, pike, mountain, and many more. But as it is mainly with the structure or architecture of land-forms that the geologist is concerned, height and dimension are of quite subordinate importance to him. Diminutive hills, for example, he must sometimes put into the same class with the loftiest mountains of upheaval. Again, certain hummocks that one may leap over, may, nevertheless, be grouped with Etna and Cotopaxi. For all hills and mountains, notwithstanding the vast range of their height and dimensions, and the infinite variety of their form and grouping, fall naturally under one or other of these two great divisions—*Original* or *Tectonic*, and *Subsequent* or *Relict* mountains.

In the former class we include every height which owes its origin either to (i.) *the piling or heaping of materials at the surface;* or to (ii.) *subterranean action which has resulted in the folding and rupturing of the earth's crust.* Subsequent or Relict mountains have originated in quite another way. They have neither been built up by accumulation at the surface, nor are they due to crustal deformation. On the contrary, they are the residual or remaining portions of former high land, mere relics or fragments of more or less

elevated tracts which have been gradually reduced in extent, and largely subdued by the forces of decay.

Of the two types of Tectonic mountains—namely, *Accumulation* and *Deformation* mountains—the first is by far the most readily understood. The structure of a typical accumulation mountain is, indeed, simplicity itself, and its origin so obvious, that no detailed descriptions and explanations are called for. With deformation mountains the case is very different, their structure being often highly complicated, and their origin sometimes obscure. We shall begin our study of mountains, therefore, by passing in rapid review the more characteristic phenomena of the simpler types.

Accumulation Mountains

With a few trifling exceptions these mountains exhibit what may be called an exogenous structure; that is to say, their growth has taken place by accretion or additions to the outside. They are of varied origin, some being due to volcanic and others to epigene or surface action. The former are much the most important, including in their number some of the loftiest heights of the globe, while those belonging to the epigene or superficial type are in general mere hills and hummocks.

VOLCANIC TYPES

Volcanoes consist of materials which have been ejected from and have accumulated around an orifice in the earth's crust. Some are composed entirely of

the debris of rocks, others are built up of sheets or masses of lava, while yet others are constituted partly of debris and partly of lava. We have thus three well-marked types of volcanoes — namely, *Debris Cones*, *Lava Cones*, and *Composite Cones*.

Debris Cones

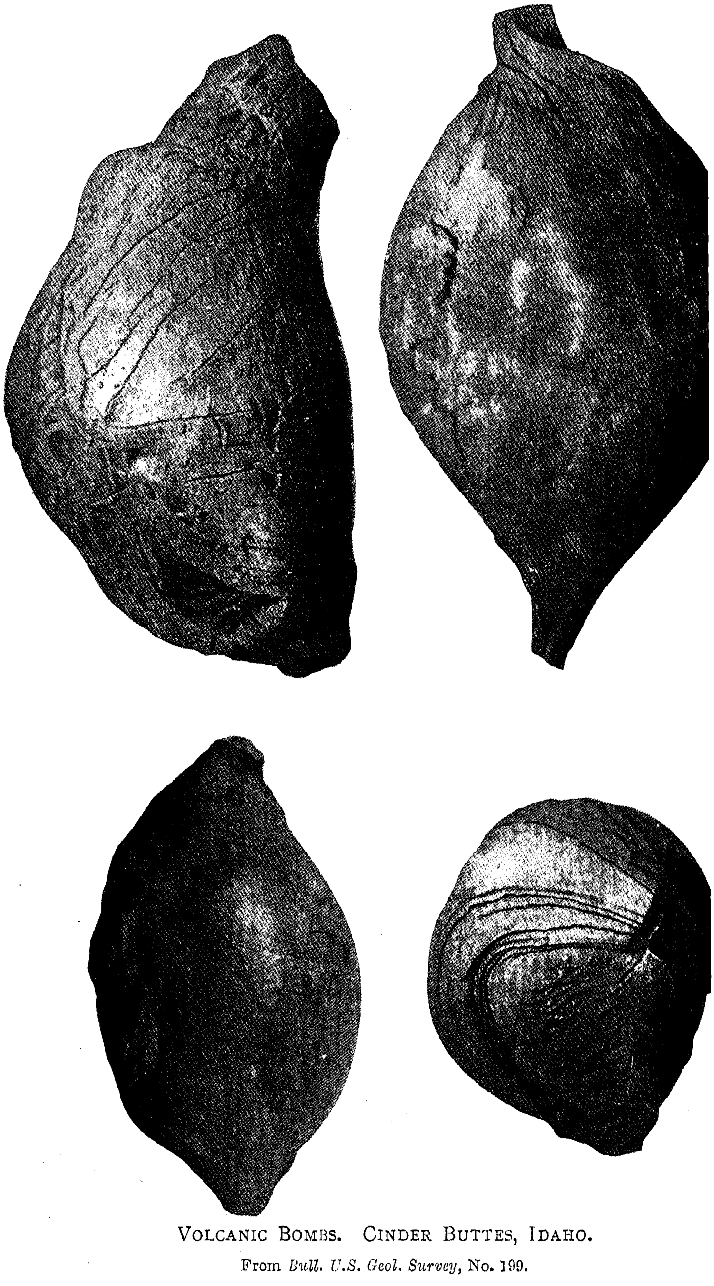
These, as the name implies, are conical aggregates of ejected rock-fragments, consisting mainly and often exclusively of slags, cinders, and comminuted materials. Not infrequently commingled with these we find chips and blocks of non-volcanic rocks, which have doubtless been torn from the walls of the chimney or funnel of eruption. Now and again, indeed, a cone may be composed largely or even entirely of non-volcanic fragments, such as greywacké, conglomerate, sandstone, shale, or limestone, or the chief constituents may be pieces of granite, gneiss, schist, or slate.

Debris cones are of all sizes. Some are quite insignificant, mere mounds, a few feet or yards in height. Such are typically represented by the *parasitical* cones now and again appearing on the surface of a flowing lava. Lavas of all kinds are more or less abundantly impregnated with vapours, immense volumes of steam being given off during volcanic eruptions. So plentifully present are these vapours that in many cases the upper portion of a lava is frothed up by them, and thus tends to acquire a slaggy and scoriaceous or cindery structure. Even after such a lava has become thickly crusted over, steam continues to escape, often very energetically,

from the underlying molten mass, occasionally rupturing the crust, and tossing up slags and cinders so as to form the small parasitical cones referred to.

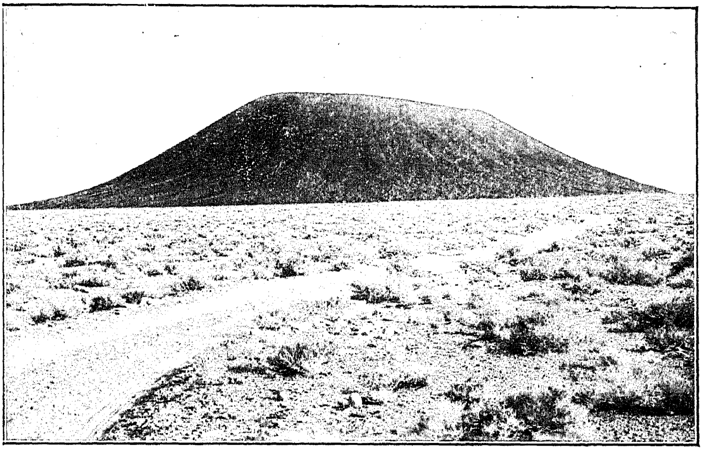
Independent cinder cones are on a larger scale, and may attain a height of 1000 feet or more. Most volcanoes of this kind are the products of single transient eruptions. A good example is furnished by Monte Nuovo on the shores of the Bay of Baiæ, which was heaped up in a few days to a height of 440 feet. Such volcanoes are of essentially the same origin as the parasitical cones just described, but differ as regards the conditions under which they are formed. Both are caused by the escape of elastic vapours from a mass of molten matter, which in the case of parasitical cones is superficial, *i.e.*, lava flowing at the surface. In the case of independent debris cones, however, the magma is subterranean, although it probably lies at no great depth. One can hardly doubt that the rise of the magma itself towards the surface is to a large extent caused, or at least accelerated, by the pressure of its imprisoned vapours. While the molten mass is being impelled upwards the solid strata above it are strained and cracked, and if they be not too thick and massive, they may suddenly yield and be tossed outwards in fragments. At the same time the cooling and partially congealed crust of the imprisoned magma, shattered by successive explosions, is rapidly ejected, while abundant red-hot clots and pasty lumps torn from the coagulating mass below are simultaneously thrown out. The general character of the slags and cinders is shown in Plate I,

PLATE II.



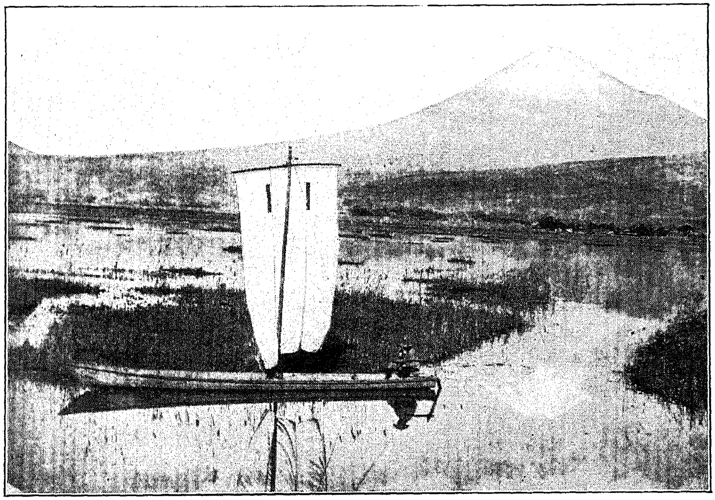
VOLCANIC BOMBS. CINDER BUTTES, IDAHO.

From *Bull. U.S. Geol. Survey*, No. 199.



1. Typical Cinder Cone, Clayton Valley, California.

Salisbury, after U.S. Geol. Survey.



2. Fuji-Yama, Japan.

Salisbury's "Physiography."

Between pages 8 *and* 9.

representing specimens taken from cinder cones in Teneriffe and Grand Canary. The clots or pasty lumps discharged from a magma are technically termed "bombs" (see Plate II). They are usually somewhat spherical or pear-shaped, but often enough quite irregular in form. Most of them are vesicular internally, and many are hollow, mere shells in fact. These "bombs" harden so rapidly during their passage through the air, that the hollow ones often break when they strike the ground.

The arrangement of its materials clearly shows that a debris cone has increased by a kind of exo-

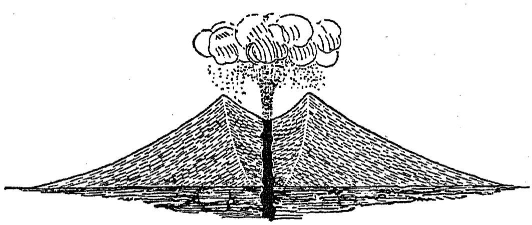


FIG. 1.—Ideal Section of a Debris Cone.

genous growth. The various ejecta have accumulated round the focus of eruption so as to form a more or less circular talus, having the same sort of structure that may be seen in any railway embankment formed by the tipping of materials down its sides. A growing cinder cone shows atop a cup-shaped depression or crater, the slopes of which converge on a central orifice of eruption. Cones of the kind, therefore, have the structure represented diagrammatically in Fig. 1. After volcanic action ceases the fragmental materials, under the influence of rain and other agents, continue to move down the external and internal slopes, which

thus in time become modified, the pipe or funnel, and even the crater itself being more or less rapidly filled up. Many small cinder cones of a geologically recent age show little or no trace of any crater, but appear as depressed mounds.

But the craters are not always so insignificant and readily filled up. Sometimes they are relatively deep. That of Monte Nuovo, for instance, sinks about 420 feet below the crest of the hill—in other words, it reaches nearly to the base of the cone. Exceptionally we encounter, as in Central Italy, the Eifel, and elsewhere, large crateral hollows, most of them now occupied by lakes, ringed round by merely an insignificant ridge of rock-fragments. Craters of that type have probably resulted from explosive eruptions of such brief duration that only small quantities of debris were thrown out, the debris consisting chiefly of fragments of the rocks that were shattered and ejected to form the cavity. Now and again these crater-lakes are not surrounded by any ridge of fragmental materials. From this some have inferred that the area of the lakes has been increased by the subsidence of their margins, and the engulfment of any ring of debris that may have existed. Possibly, however, the absence of any ridge of debris may be acounted for by the extreme energy of the escaping vapours, the ejected materials having been scattered broadcast over the surrounding country.

Debris cones are usually rather abrupt or steep (Plate II*a*, 1), but exceptionally they are somewhat

depressed, their flanks falling away gently in all directions. The difference is due chiefly to the character of the fragmental materials. When these consist of an aggregate of large rough slags, cinders, and blocks, whose angle of repose is naturally high, the cones may slope at angles of 35° to 40°. But when a cone is composed mostly of much smaller fragments—mere lapilli commingled with gritty and ashy matter—the slopes are correspondingly gentle. In each case, however, the structure is the same, the configuration or external form being always the direct expression of that structure. In a word, the dip of the layers and the inclination of the surface coincide.

Cones of the kind we have been considering are often distributed over the flanks or round the base, or even athwart the broad craters of extensive lava-producing volcanoes; at other times they occur independently, either isolated or in groups. In the latter case they may appear at irregular intervals, strung as it were along a line, or several more or less parallel lines, running in some particular direction. Or one chain of cones may cross another similar chain at various angles. Such chains, we can hardly doubt, indicate the presence of ruptures or fractures of the crust; and most of the important volcanoes of the world, as we shall subsequently learn, appear to be similarly connected with dislocations. But although volcanic eruptions of all degrees of intensity would seem most frequently to take place along such lines of weakness, yet many of the smaller cones are apparently independent of any pre-existing dislocations or

faults as they are technically termed. It can be shown that certain isolated cones, and now and again even irregular groups of cones, have been heaped up around apertures which have been drilled or punched through the crust, or blasted out by explosive vapours. Probably none of the cones we have been considering are of deep-seated origin. They all point, as already indicated, to the presence of a magma at no great distance from the surface, the steam escaping from which takes advantage of any fractures that may chance to be present, or bursts its way through cracks and fissures caused by the upward pressure of the magma itself.

Lava Cones

Certain relatively small volcanoes are built up exclusively of formerly molten rock or lava, and the same is occasionally the case with volcanoes of the grandest dimensions, in the construction of which loose ejecta play a very subordinate part. Some lavas are very viscous and pasty at the time of their emission, others are more fluid. The form of a lava cone, therefore, is determined very largely by the character of the lava. The relative fluidity of a molten rock depends on the composition and temperature of the latter. Basic lavas, that is lavas with a low percentage of silica, are the most fusible, while acid lavas, with a larger proportion of silica, are the least fusible. Other things being equal, therefore, basic lavas might be expected to be more fluid than

acid lavas. It is probable, moreover, that basic lavas are the hottest. Be that as it may, it would seem that basic lavas are apt to flow rapidly away, and to spread outwards as relatively broad sheets, while acid lavas move more sluggishly, and tend to form narrow *coulées*, or, as not infrequently happens, they coagulate and stiffen in immediate proximity to the focus of eruption.

(*a*) *Cones of Viscous Lava.*—Among the most notable examples of viscous lava-cones are the volcanic hummocks or "mamelons" of the Ile de

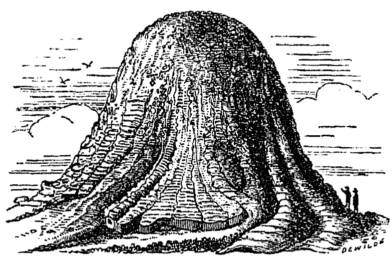


FIG. 2.—"Mamelon Central." (Bory de St Vincent.)

Réunion or Bourbon, and the trachytic bell-shaped domes of Auvergne. The concentric or onion-like structure of such volcanoes shows that the sluggishly-flowing lava has solidified immediately around and above the orifice of eruption. In some of the Bourbon mamelons the lava wells out more or less continuously and quietly from a central focus, the viscous streams congealing as they creep outwards and downwards, so that the cone increases in height and extent by irregular concentric coatings. Fig. 2 shows the "Mamelon Central," described by Bory

de St Vincent, as 160 feet in height; its structure being represented diagrammatically in Fig. 3. Occasionally, however, a mamelon may show a crateral hollow atop (Fig. 4). In other cases the structure is

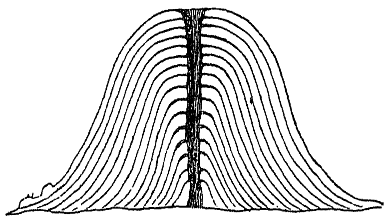


FIG. 3.—Ideal Section of "Mamelon Central."

rather endogenous than exogenous, the viscous lava instead of welling out in successive streams, one over another, has piled itself up immediately over the orifice. Professor Reyer has illustrated eruptions of

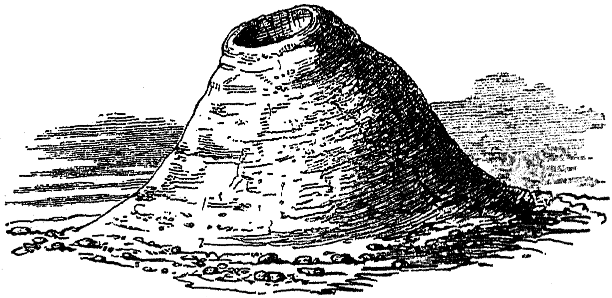


FIG. 4.—Mamelon with Crater. (Bory de St Vincent.)

this kind by forcing upwards through a hole in a board variously coloured plaster of Paris in a pasty state. The plaster, as it was gradually and continuously squeezed out, accumulated over the hole in the form of a rounded boss or cupola, which, when bisected, showed by the disposition of its differently-

coloured bands, a well-marked concentric endogenous structure (see Fig. 5). Such is generally believed to have been the mode of origin of the curious domes and bell-shaped protrusions of trachyte so conspicuous in Auvergne and certain other regions of

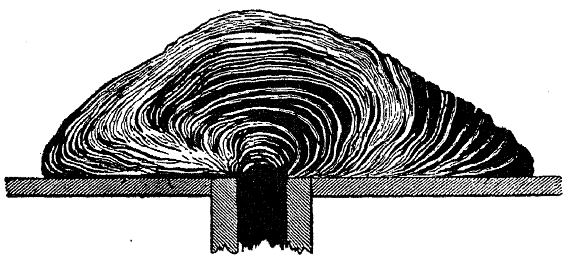


FIG. 5.—Experimental Illustration of the Mode of Formation of a Cone of Viscous Lava. (After Reyer.)

extinct volcanoes (see Fig. 6). Many of the cones and domes referred to are mere hills, some 50 feet or less in height, but others attain much larger dimensions. Puy de Dôme, for example, rises not less

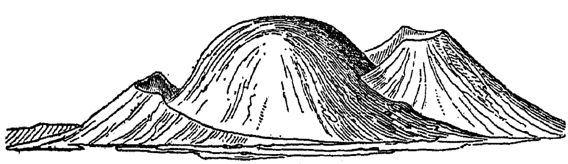
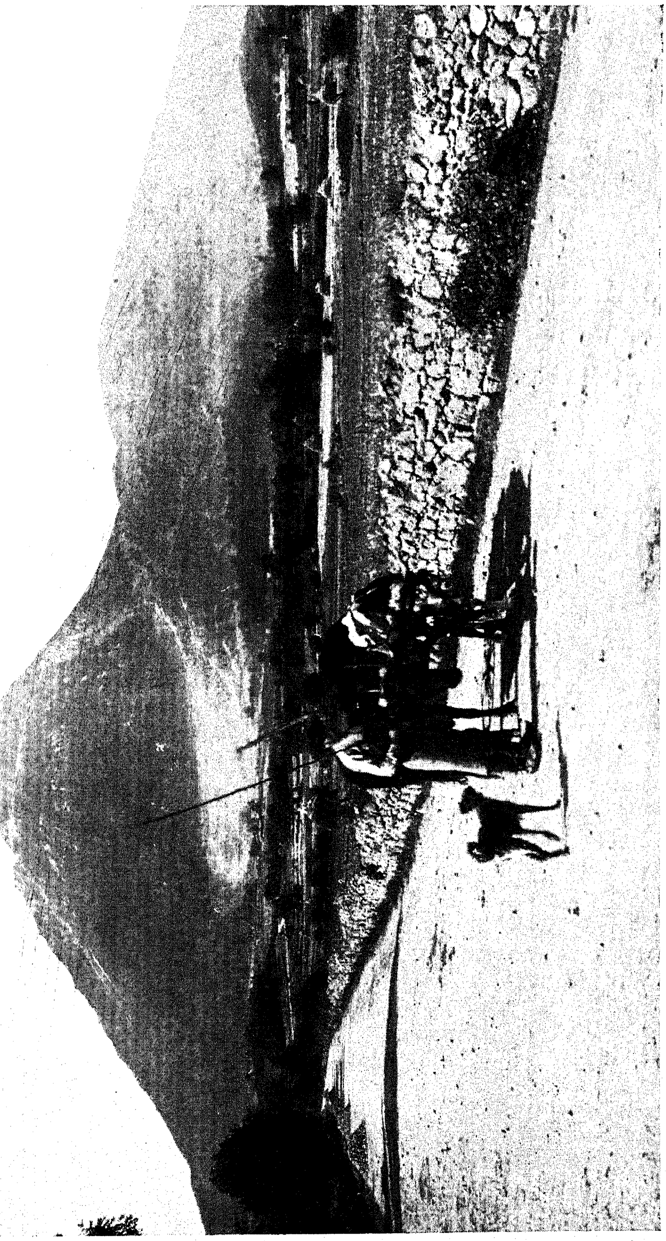


FIG. 6.—Grand Puy de Sarcouï—a dome of trachyte rising between two debris cones. (P. Scrope.)

than 1700 feet above the general level of the plateau on which it stands (see Plate III).

(*b*) *Cones of Liquid Lava.* — The grandest examples of this type are the great volcanoes of the Sandwich Islands. Their eruptions are relatively tranquil, the lavas flow rapidly away and tend to spread out as broad sheets; and as they are not

usually accompanied by the discharge of loose ejecta, they have gradually built up vast shield-shaped eminences, covering areas many square miles in extent, and rising to heights of more than 10,000 feet. Hawaii, 93 miles long and 80 miles broad, appears to consist wholly of volcanic materials, derived from several foci. The main mass of the island, however, is made up of only four great flattened cones—Mauna Kea, now extinct; Mauna Hualalai, dormant since the beginning of last century; Mauna Loa and Kilauea, both in frequent eruption. Of these the loftiest is Mauna Loa, with an elevation of 14,000 feet, and Mauna Kea is about the same height. The crater of the former is correspondingly large, being three miles long, two miles broad, and about 1000 feet deep. As cinders are only sparingly ejected from this volcano, its summit does not taper upwards rapidly, as is the case with volcanoes from which fragmental materials are abundantly discharged. On the contrary, it is almost flat atop, the surface sloping outwards from the lips of the enormous crater at an angle of not more than 3°, for a distance of one or two miles, after which the slope increases to 5° or 8°. The huge volcano may, therefore, be described as a much depressed cone, having a diameter of about eighty miles. Its mere elevation above the sea does not, however, give its actual height, for Hawaii with its volcanoes rises from a depth of 18,000 feet. Mauna Loa and its sisters, therefore, are among the loftiest mountains of the globe, for, when measured from the ocean-floor—their true base—they exceed



PUY DE DÔME, NEAR CLERMONT, AUVERGNE. [An Extinct Volcano composed of Trachyte.]

Photo, Detroit Pub. Co.

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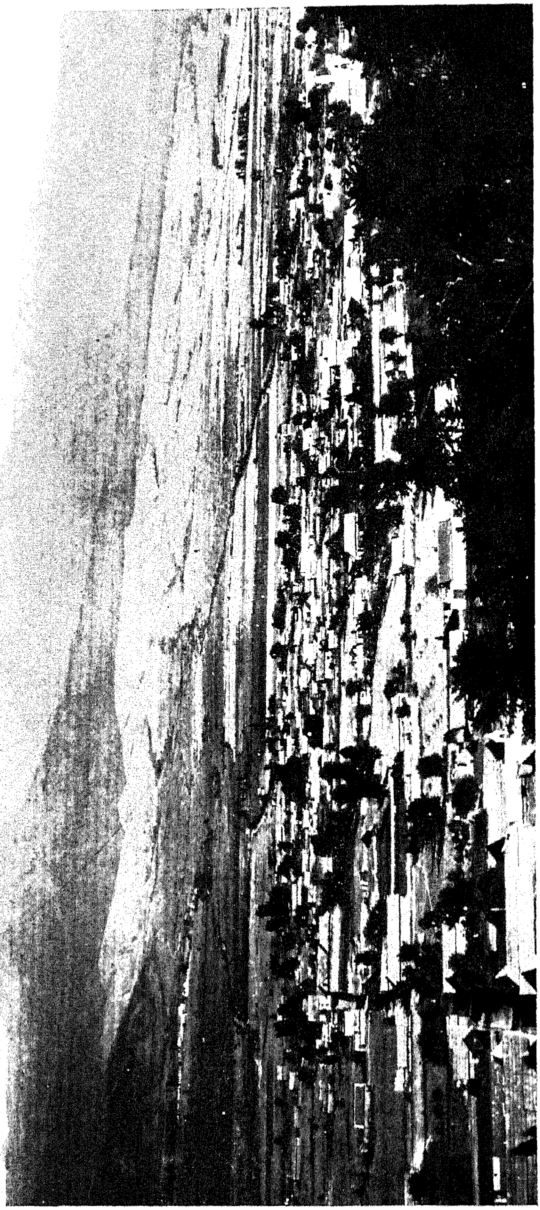
PLATE IV.



POPOCATEPETL (A COMPOSITE VOLCANO), FROM SACRAMENTO, MEXICO.

Photo, Detroit Pub. Co.

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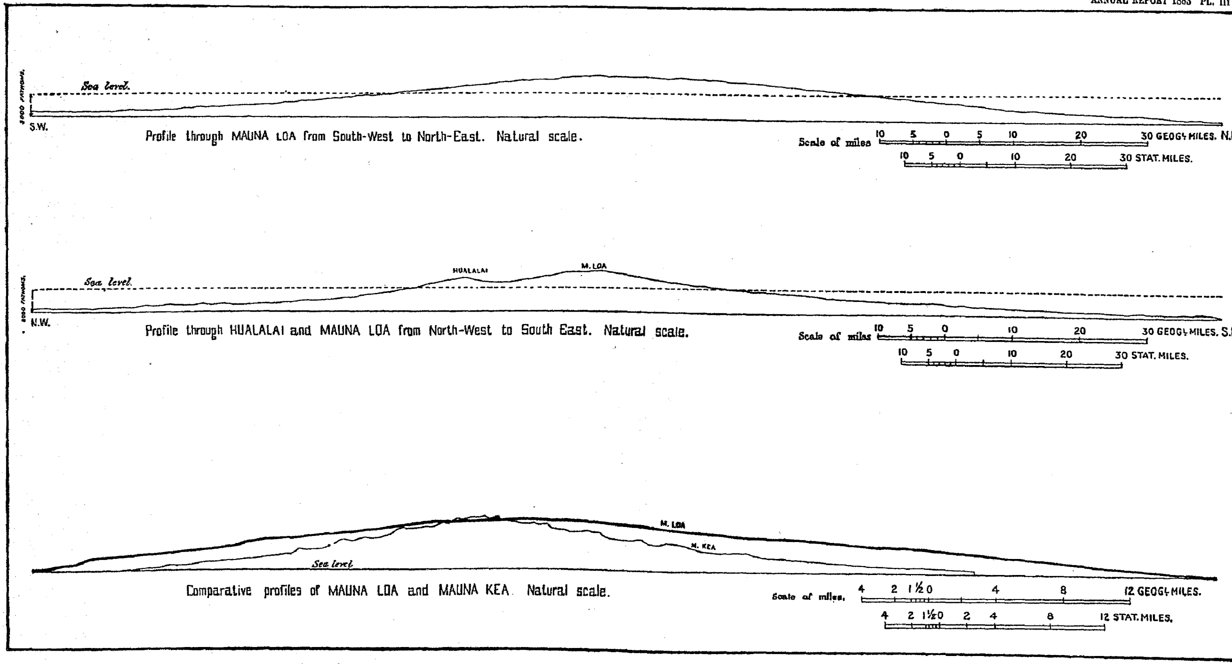


FIG. 7.—Profiles of the Great Lava Cones of Hawaii.

30,000 feet in height. The profiles of these mountains are shown upon a true scale in Fig. 7 (p. 17).

Composite Cones

The great majority of active volcanoes emit both loose ejecta and lava, and the same would seem to have been the case with most dormant and extinct volcanoes. Some composite cones consist chiefly of cinders; they are, in short, debris cones from which it may be only one stream of lava has flowed. Many such occur in close association with the typical debris cones already described, and, like them, they are

FIG. 8.—Debris Cones breached by the Outflow of Lava. (Scrope.)

frequently the products of single transient eruptions. Their life-history is easily read in their structure. After slags, cinders, and bombs have for some time been ejected and a cone formed, the lava rises in the pipe or funnel, and may accumulate in the crater until, under the increasing weight and pressure of the mass, the side of the cone gives way, and the molten rock escapes through the breach. In most cases the outflow of the lava is succeeded by another and feebler bombardment of ejecta, and then the volcano becomes extinct. Cones of the kind occur in many volcanic regions, as in Auvergne (Fig. 8), Italy, the

Canary Islands, and elsewhere. Between this simple type and the largest composite cones, all degrees of complexity are met with. Some volcanoes, for instance, are the products of only a few more or less energetic eruptions, separated the one from the other by longer or shorter intervals of repose; while others bear witness to a protracted succession of similar eruptions, and therefore attain correspondingly greater dimensions. All, however, are built after the same pattern.

In the ordinary eruptions of large composite volcanoes, the succession of events is just the same as in the case of the simpler type, namely, first a discharge of loose ejecta, next the outflowing of lava, and finally another discharge of fragmental materials. It is by the repetition of these phenomena that volcanoes continue to grow. As the loose ejecta necessarily accumulate in greatest abundance immediately around the orifice of eruption, all composite cones tend to taper more or less rapidly towards the summit. The lava naturally escapes where the crater-rim is lowest, and as this rim is liable to frequent modifications, the molten rock of successive eruptions flows away now in one direction, now in another. The final result, then, is the formation of a conical mountain built up of irregular and relatively narrow sheets of lava, rudely alternating with more widely spread accumulations of debris. The lavas and the accompanying layers of ejecta vary indefinitely in extent and thickness, some of the former having flowed as narrow *coulées*

for no great distance down the flanks of the volcano; while others may have descended to the base of the cone, and streamed far out as broad sheets upon the low ground beyond. If the course of a lava-flow be restricted, such is not the case with fragmental ejecta. These usually are distributed all round the volcano, the larger slags, cinders, bombs, and blocks gathering most abundantly in proximity to the crater, while the smaller stones (lapilli), grit, and ashes tend to be more widely scattered. Thus after a long period of activity a volcano assumes a very characteristic outline. From the lip of the crater outwards the slope is at first steep, the gradient—about 30° or more—being that of a typical cinder cone. As the distance from the crater increases, however, the inclination constantly diminishes, until towards the base it passes to horizontality. The graceful curve of a typical composite cone is well illustrated by the famous Fuji-Yama of Japan (Plate II*a*, 2), the shapely Cotopaxi of Ecuador, and the majestic Popocatepetl of Mexico (Plate IV).

Cones such as these owe their perfection of outline to the eruptions having apparently taken place persistently from one central focus. The symmetry of a cone, however, is liable to be disturbed by various causes. For instance, lava and loose ejecta instead of issuing from the summit crater, now and again escape through rents opened at various heights on the flanks of a volcano, and the continuous curve of the mountain becomes in this way interrupted by the growth of lateral cones

of larger or smaller size. Should the wind blow somewhat constantly in one direction, the loose ejecta will fall most abundantly upon the leeward slopes, and thus tend to make the mountain lopsided. The deluges of rain that almost invariably accompany eruptions have likewise a modifying influence, the mountain sides becoming deeply scored and furrowed by torrents. But so long as a volcano continues active, the modifications of the surface caused by such erosion hardly affects the symmetry of the growing mountain. The ravages of rain and torrents are more than made good by recurrent discharges of lava and debris.

The most important changes to which a composite cone is liable are brought about by the action of the volcano itself. After a long succession of ordinary or moderate eruptions a crisis in the history of the volcano arrives. Paroxysmal energy is developed, and the cone, which it may have taken long ages to build, is suddenly decapitated. The whole upper part of the mountain disappears, having apparently been blown outwards in fragments. Not improbably, however, the truncation of the cone may be due in some measure also to undermining and collapse, caused by the enormous discharges of material that characterise paroxysmal eruptions. It is quite conceivable, indeed, that a cone may become eviscerated by the escape of vast volumes of lava from fissures in its flanks or towards its base—the upper part of the mountain deprived of support thereupon giving way, and plunging into the

abyss left by the outflow of the lava. Such is supposed to be the origin of the great cauldron-like depression now occupied by Crater Lake, the most remarkable feature of the National Park, Oregon. The lake measures five or six miles in width and 2000 feet in depth. Its rim consists of volcanic rocks, inclined outwards in all directions and obviously forming the basal portions of what must have been a great volcano. It is believed that the upper part of the cone ("Mount Mazama") probably rose to a height of 6000 feet higher than the surface of the lake which now replaces it, and the amount of material engulfed by its collapse must have equalled seventeen cubic miles. American geologists are agreed that the cone could not have been shattered and blown outwards by any paroxysmal explosions, for there is no trace of an encircling ridge of fragmental materials. According to Mr Diller, who carefully surveyed the region, if Mount Mazama had been blown away, and the debris equally distributed upon the outer slope of the rim within three miles of the crest, it would have made a layer over 1000 feet in thickness. Mr Diller remarks that such a mass would be so conspicuous and composed of fragmental materials of so pronounced a character that its presence could not be a matter of doubt. It would seem evident, therefore, that Mount Mazama disappeared by subsidence. Strange to say, however, no trace has yet been found of the immense volumes of lava which must have streamed out somewhere, and so

brought about the evisceration and collapse of the mountain.

After a paroxysmal eruption, which so frequently results in the truncation of a cone, a volcano may remain dormant for an indefinite period, or it may die out altogether. Among many examples that might be cited we may refer in a word to the great truncated cone of Palma, one of the Canary Islands. The extensive and profound central depression of this extinct volcano, called "La Caldera," measures three to four geographical miles across, and is surrounded by an almost unbroken wall of abrupt pine-clad slopes, backed by gaunt precipices of volcanic rocks that tower to a height of 5000 feet over the floor of the Caldera and 7000 feet above sea-level. The only opening in this vast crater-ring is on the south-west of the Caldera, where a torrent, fed by innumerable streams, dashes through a deep barranco or rocky gorge to the sea. The accompanying map of Palma (Plate V) is an outline of the Admiralty Chart by Captain Vidal.

Palma has become extinct, but many volcanoes have been similarly eviscerated, and after more or less prolonged repose have manifested renewed activity, and commenced to build up one or more new cones within their calderas. This cone-in-cone structure is well illustrated by Vesuvius, the existing volcano having grown up within the great cauldron-like depression of the shattered cone of Monte Somma. The present orifice of eruption opened not quite in the centre but towards the southern margin of that

depression. In consequence of its excentric position the younger volcano has gradually buried a considerable portion of the old crater-ring, and filled up the southern part of the caldera. On the other side, however, where less accumulation has taken place, the caldera extends from the base of the Vesuvian cone to the steep cliffs of Monte Somma—the surviving relics of the prehistoric crater-ring.

The Peak of Teneriffe furnishes another example of similar phenomena on a grander scale. The approximately circular caldera of this mountain measures eight miles across, and is rimmed by a precipitous crater-ring, the higher points of which reach

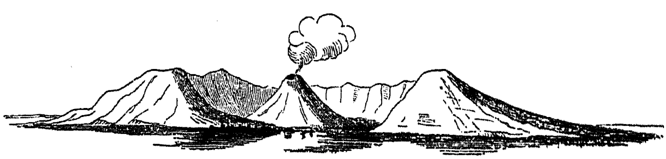
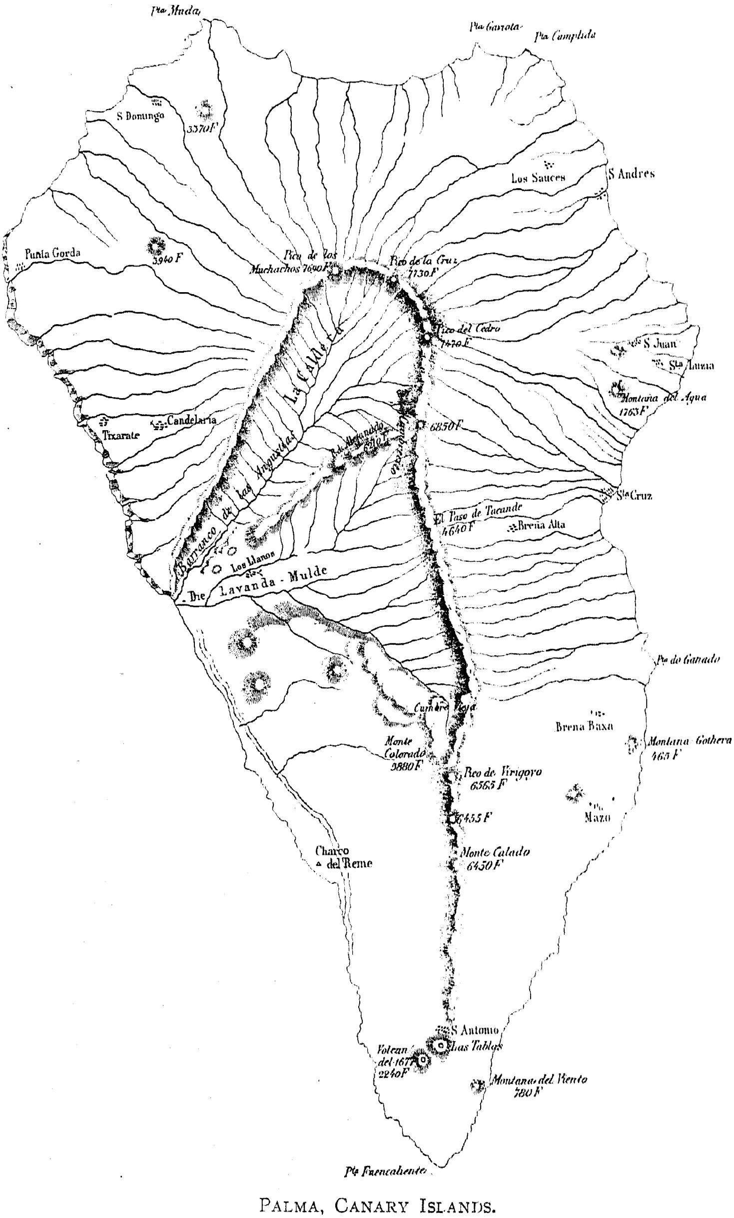


FIG. 9.—Barren Island, Bay of Bengal, showing cone-in-cone structure.

2000 feet above the floor of the great basin. As is frequently the case with other volcanic mountains of the same type, the precipitous crater walls are breached in several places; in short, the rim of the caldera is here and there strongly notched. Two lofty cones, the famous Peak and the somewhat less important cone of Chahorra, with which a number of much smaller cones are associated, appear within the encircling crater-ring.

The cone-in-cone structure is not less well exemplified in the case of partially submerged volcanic mountains. Barren Island, in the Bay of Bengal, for

PLATE V.



PALMA, CANARY ISLANDS.

Captain Vidal

MOUNT SHASTA, CALIFORNIA.

[An Extinct Composite Volcano furrowed by Erosion.]

Photo, Detroit Pub. Co.

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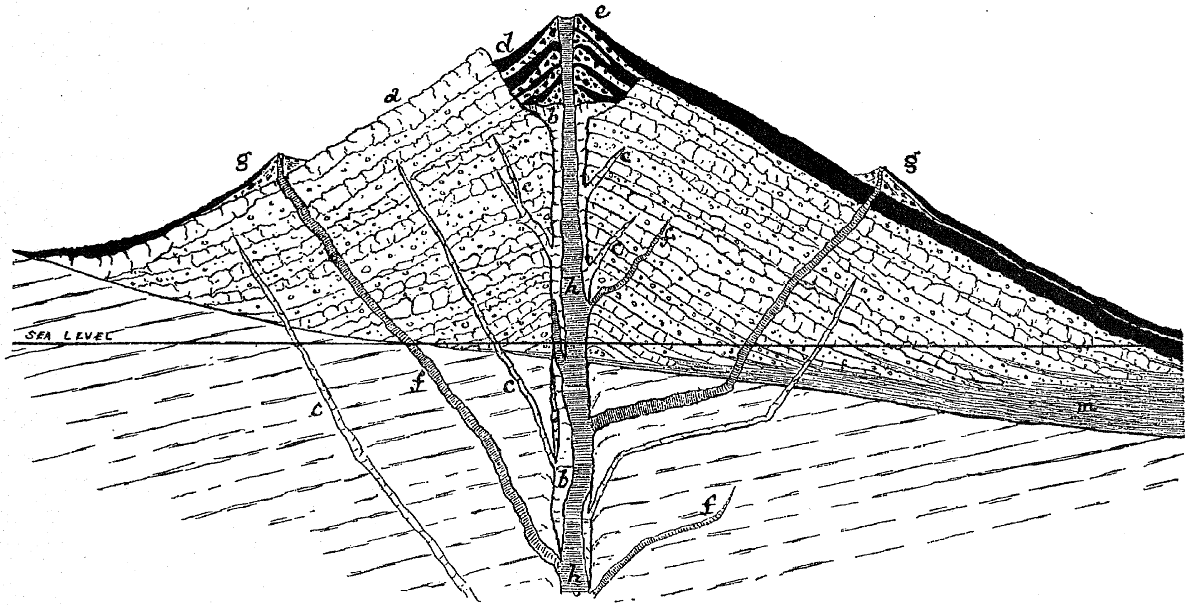


FIG. 10.—Diagrammatic Section of a Volcano, showing Cone-in-cone Structure. *a*, Old cone of first period of volcanic activity; *b b*, pipe of old cone plugged up with lava; *c c*, dykes of first volcanic period; *d*, crateral hollow occupied by cone (*e*) of second volcanic period; *h h*, pipe of second period plugged up with lava; *f f*, dykes of second period; *g g*, parasitic cones; *m*, marine deposits interstratified with volcanic products.

instance, consists simply of an extensive crater-ring. The ring, several miles in diameter, is breached at one point where the sea enters the caldera and forms a lagoon, within which a central active volcano rises to a height of 4000 feet (Fig. 9, see p. 24). Santorin in the Grecian Archipelago is another example of the same kind.

As paroxysmal eruptions have occurred again and again in the case of many considerable volcanoes, it is probable enough that even the most perfect cones which exhibit no trace of cone-in-cone structure may nevertheless have repeatedly passed through alternate stages of destruction and renovation. Should Vesuvius continue to erupt for a prolonged period, it may eventually fill up entirely the old caldera of Monte Somma, bury the last traces of the prehistoric crater-ring, and discharge not only loose ejectamenta but streams of lava down its northern slopes. The cone-in-cone structure would then cease to be recognisable.

The accompanying diagram may serve to illustrate the more important structural features of a composite volcano (Fig. 10, see p. 25).

CHAPTER II

ORIGINAL OR TECTONIC MOUNTAINS—*continued*

Decay of Volcanic Cones; Volcanic "Necks" of Scotland; Geyser Cones; Air Volcanoes.

Decay of Volcanic Cones

HITHERTO we have been considering the mode of origin of certain mountains of accumulation, and have assured ourselves that the form or configuration of active, dormant, and recently extinct volcanoes is a more or less exact expression of their geological structure. We have recognised, however, that even during the period of growth a volcano is liable to denudation, that loose ejectamenta of all kinds tend to be washed down, while rapid torrents tear out gorges and ravines in the flanks of the mountain, and overspread the low grounds with their spoil. Nevertheless, the growth of an active volcano is hardly impeded by this constant waste, for the rate of increase exceeds that of decay. But as old age approaches, and eruptive energy waxes feebler, and at last ceases altogether, the ravages caused by epigene action become more and more evident; in short, the mountain begins to lose its original con-

figuration, and slowly or rapidly, as the case may be, crumbles away.

The numerous extinct volcanoes of the world exhibit every stage in this process of degradation. In many cases the cone-like form still persists, although profoundly furrowed by innumerable gullies and gorges; in other cases the original symmetry has entirely disappeared; while in yet others, only a few low hills, or merely a single abrupt knoll may be left to mark the site of a formerly lofty and extensive mountain. From the geological point of view the final destruction of a volcanic cone is seldom a protracted process, for the structure is relatively weak, the usually steep inclination of the constituent layers away from the centre of dispersion greatly favouring denudation. Many volcanoes, it is true, are traversed by numerous dykes which act as stays to strengthen and support the structure (see Fig. 10). But while these may impede the work of demolition, they cannot arrest it; sooner or later the mountain must succumb.

The form assumed by a volcano during its decay necessarily varies according to the prevalent character of its constituents. A cone composed largely or exclusively of coarse slags and cinders, for instance, will retain its form longer than one of similar size made up entirely of fine-grained ejectamenta, with or without accompanying beds of lava. Rain falling upon a mass of coarse scoriæ is at once absorbed—no superficial water-flow is possible. Not until the cinders are reduced to the condition of grit

and clay by the chemical action of rain, aided, it may be, by the mechanical action of frost, can a scoria cone be much affected by denudation. On the other hand, a debris cone consisting of fine-grained and less pervious materials offers slighter resistance to epigene action; rain washes over and rapidly lowers its surface. But cones which are neither sufficiently high nor extensive to nourish springs, or to be provided with torrents, may retain their original shape for long periods of time.

Considerable diversity of form is exhibited by the more or less worn and denuded debris cones of one

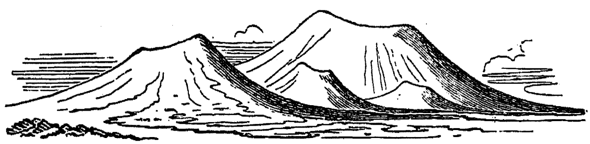


FIG. 11.—Denuded Debris Cones—craters not obliterated. (Scrope.)

and the same district. In some the cone with its crater may be well preserved (Fig. 11), while others have been reduced to mere amorphous masses of cinders and lapilli, rising feebly above the general level of the ground, and between these extremes all gradations occur. The accompanying illustrations (Fig. 12 A) give the outlines, on a true scale, of several of the cinder cones that form the volcanic chain of Velay, central France. Mont-le-Bar, it will be noticed, is tolerably well preserved, the crateral hollow being still conspicuous, while in the other cases it has been obliterated. The highest cones represented show slopes not exceeding 15° to 18°, but

those which have been greatly lowered by denudation are less steeply inclined. These differences are due in chief measure to the varying character of the constituent materials, the rocks of some cones being more closely compacted, harder, and thus less readily

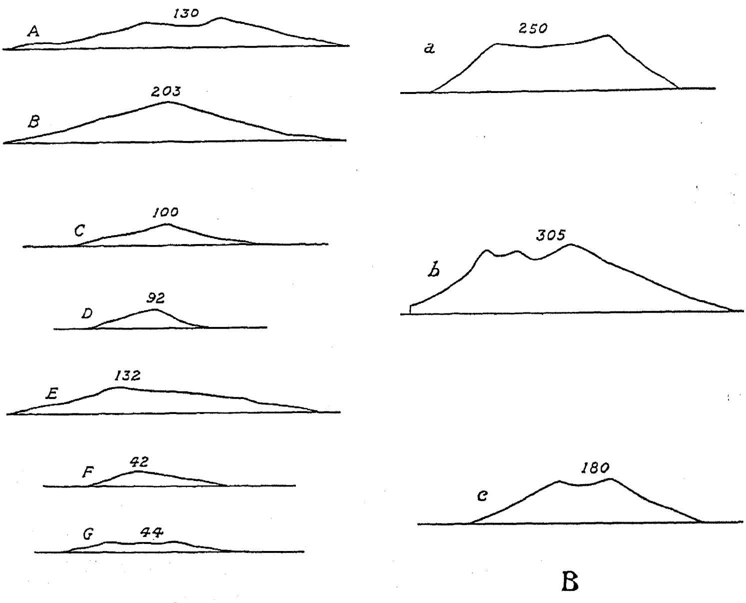


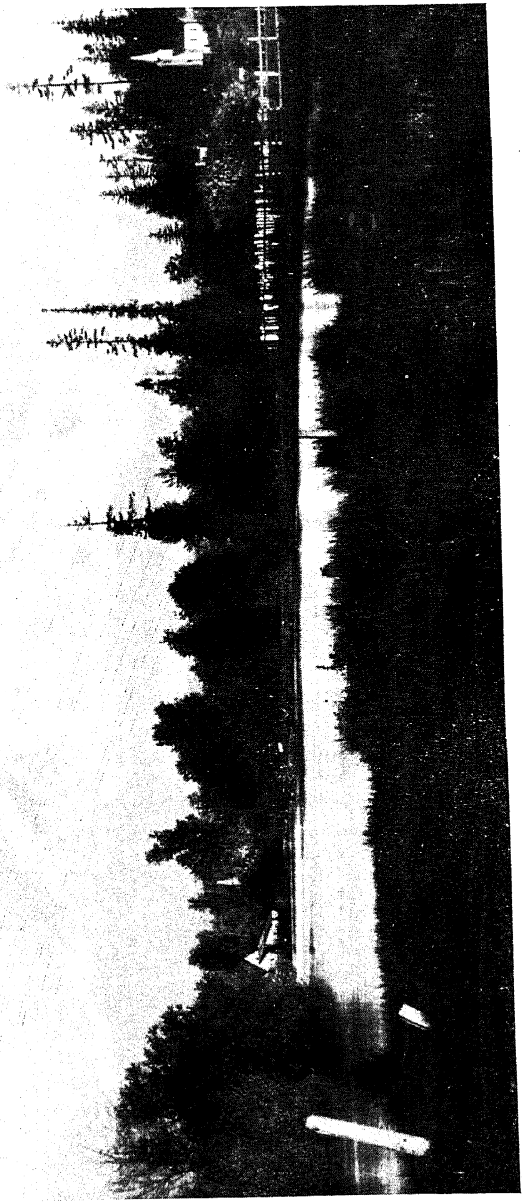
FIG. 12.—Cinder Cones, Velay (A) and Auvergne (B), Central France. (After M. Boule.) A, Mont de Bar; B, Briançon; C, La Durande; D, Suc d'Alleyras; E, Le Coupet; F, Croustet; G, Fix-St-Geneys; *a*, Puy de Louchadière; *b*, Puy de Côme; *c*, Puy de Marmont. The figures denote the height (metres) of the cones above their base.

reduced than those of others. The process of degradation is in many cases accelerated by the opening and shifting of superficial rents in such cones as are composed of partially consolidated or less compacted materials.

For purposes of comparison the outlines of three

notable puys of Auvergne are given (Fig. 12 B). The latter, it will be observed, are in a better state of preservation than those of Velay, their slopes attaining an angle of 35°. The Velay cones, on the other hand, are all much depressed, some of them (such as those of Le Croustet and Fix-Saint-Geneys) being reduced to mere lenticular sheets of lapilli and cinders.

The peculiar lava cones of central France show, in like manner, different degrees of preservation, although all belong to the same period of volcanic activity. Thus the characteristic dome-shape, so well conserved in the Grand Puy of Sarcoui (see Fig. 6, p. 15), has been considerably modified in Puy de Dôme. The constituent trachytic rocks, owing to their variable constitution and structure, have yielded somewhat unequally to epigene action. In certain places their extreme porosity has favoured disintegration and crumbling, while elsewhere a closer-grained texture has impeded denudation. Hence broken and rugged outlines and smooth gently-curved surfaces may be observed in different parts of one and the same dome-shaped hill. Owing also to the concentric structure of the trachyte which is occasionally well developed, the outer envelope of the rock has sometimes been partially removed, a kind of exfoliation on the large scale. In the case of the Puy de Cliersou, for example, that bell-like cone is crowned with a circular and flattish capping which terminates on the brow of the hill in a ring of broken rocks. According to Scrope, "this capping appears to be the remains of



MOUNT RAINIER (OR TACOMA), WASHINGTON, U.S.A.
[An Extinct Composite Volcano—Snow-capped and supporting Glaciers.]
Photo, Detroit Pub. Co.

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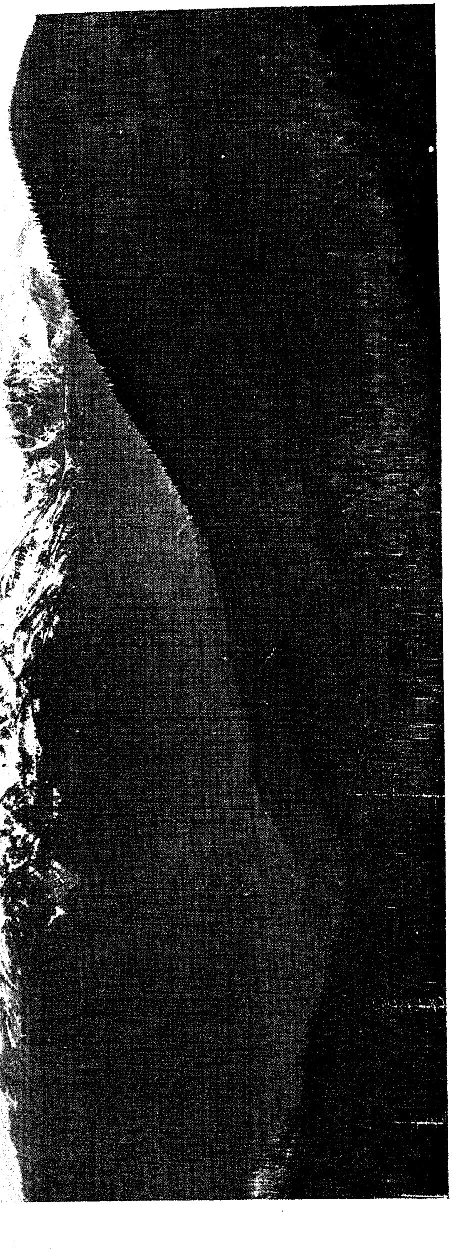
PLATE VIII.



MOUNT HOOD, OREGON, U.S.A.

[An Extinct Composite Volcano, much eroded, and supporting Glaciers.]

Photo, Detroit Pub. Co.

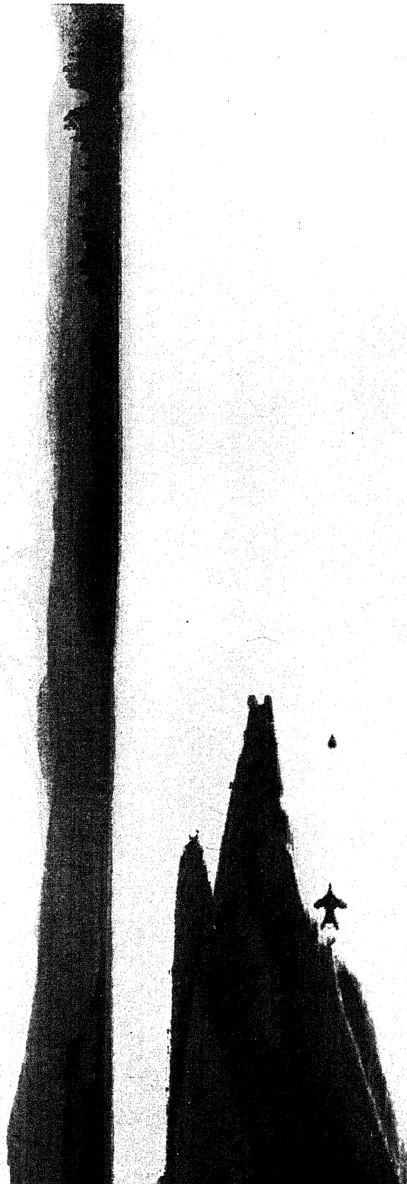
[*To face page* 33.

feet), one of the best-known summits of the Cascade Range, in Oregon (See Plates VIII and IX). A still more advanced stage in the decay of volcanoes is well illustrated by many an island in the Pacific. Professor Dana has made special reference to the island of Tahiti (Plate IX*a*, 1), which consists of two long extinct and highly denuded volcanoes—the larger one of which forms the northern and most considerable part of the island. Originally it existed as a depressed cone of the same type as the Hawaiian volcanoes, rising to a height of probably not less than 8000 feet, and sloping outwards in all directions at an average angle of 8°. Now it is a thoroughly dissected mountain; profound valleys trench its flanks and lay bare the heart of the old volcano to a depth of 2000 to nearly 4000 feet. So active has been the erosion that the numerous deep valleys, which radiate in all directions from the centre of the island, have been widened to such an extent that they are separated from each other by mere narrow ridges—often not more than a foot or two in width atop. It is needless to say that all traces of a crater have disappeared. But however much Shasta, Rainier, Mount Hood, and even Tahiti have suffered from epigene attack, each nevertheless retains its individuality, and can still be recognised for what it is — an extinct volcano; from Rainier and Mount Hood, indeed, hot vapours still issue. Such, however, is no longer the case with an old volcano, the relics of which are known as Marysville Buttes, in California (see Plate IX*a*, 2). The buttes in question form a number of

rugged and fantastic hills, grouped in a circular cluster ten miles in diameter, and rising 1700 to 2000 feet above the level of Sacramento River. The volcanic cone of which they are the surviving remnants must have attained a considerable size, perhaps rivalling Vesuvius in its dimensions; but to such an extent has it been dissected and worn down that its very foundations are exposed, so that one can see the shattered sedimentary strata through which the lavas and loose ejectamenta were discharged.

Although Marysville Buttes are the mere *disjecta membra* of a volcanic cone, it is still possible, from their appearance and disposition, to form some conception of the height and dimensions of the original mountain. In many cases, however, the demolition has been so complete, that not a vestige of the cone may remain, the only evidence of the former existence of a volcano being the plug of igneous rock that consolidated in the old pipe or funnel of eruption. Cores or roots of this character are common in many lands where volcanic action ceased to manifest itself in ages incalculably remote. In Scotland, for example, numerous isolated crags, rounded hills, and abrupt towers of rock indicate the sites of cones which came into existence during the far past Palæozoic period. Many of these would seem to have been mere monticles, like the cinder cones of Auvergne, but others must have attained some size. As a rule it is only the plugged-up pipe or funnel which has been preserved (Figs. 13, 14, 15), but now and again a portion of the cone also has survived.

PLATE IX.



MOUNT HOOD, OREGON, U.S.A.
Photo, Detroit Pub. Co.

[*To face page* 35.

Some of these old Scottish volcanoes erupted on land, while others, and probably the larger number, were submarine. All had become extinct and suffered excessive waste before the close of Palæozoic times. Not only so, but most of them were eventually buried on the sinking sea-floor under vast accumulations of

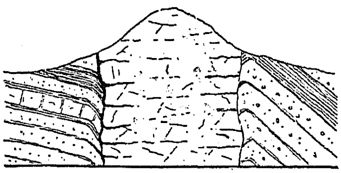


FIG. 13.—"Neck," or funnel of old volcano, plugged up with basalt.

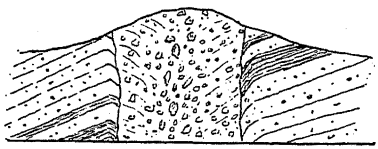


FIG. 14.—"Neck" filled up with agglomerate.

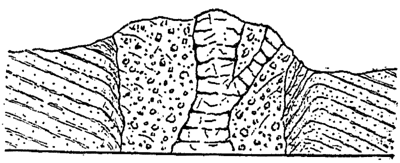


FIG. 15.—"Neck" occupied by agglomerate and basalt.

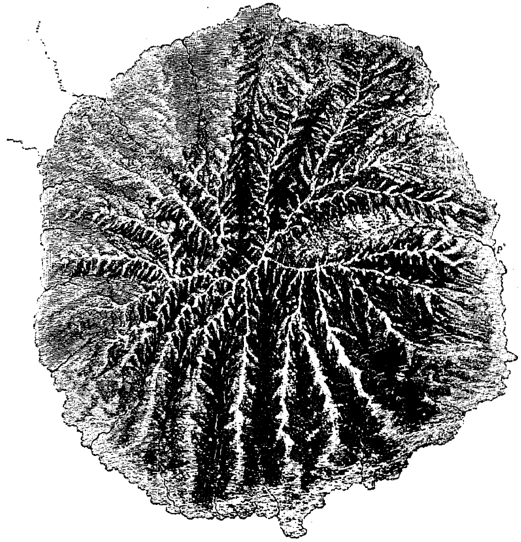
sand and mud (now sandstones and shales). Subsequently the Scottish area reappeared as dry land, and during a protracted period of denudation the relics of the ancient volcanoes were gradually laid bare, and again exposed to degradation. Owing, however, to the superior durability of their constituent rocks, they have been worn down less readily than the sandstones, shales, and other sedimentary formations that surround them. Consequently they now appear as conspicuous features in a landscape.

Some of the Scottish "necks," as they are called,

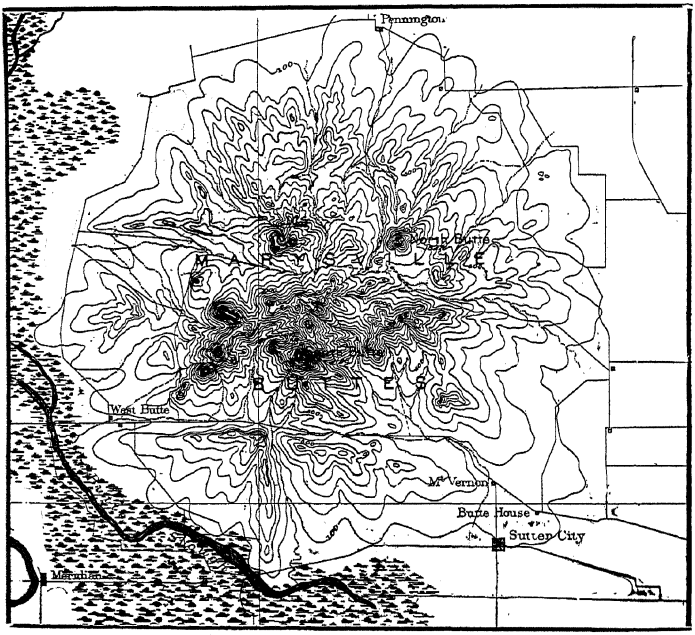
apparently represent the plugged-up vents of what must have been notable volcanoes, for they are not infrequently associated with considerable lavas, and thick sheets of what were formerly loose ejecta. This is the case with not a few of the older vents, those, namely, that date from early Carboniferous times, such as Arthur Seat and North Berwick Law (Plate X). The vents in question often appear as conspicuous hills, especially when the material occupying the old funnel or pipe of eruption is of harder consistency than the rocks of the same neighbourhood. Frequently the plug, as in the case of North Berwick Law, is a massive crystalline igneous rock; or just as often it is an aggregate of angular or subangular blocks, or the vent may be occupied by both kinds of rock together. From the distribution of these particular "necks," and the trend of their associated lavas and tuffs, we gather that ejections sometimes took place from chains or lines of contiguous volcanoes and sometimes from irregular groups of cones. Eruptions occurring now here, now there, on the slowly sinking floors of lagoons and seas, broad volcanic banks were gradually built up, which, on the re-elevation of the region, formed undulating plains and plateaux. These, it is needless to say, must have been much more extensive than the hilly tracts that now represent them.

The later stages of the Carboniferous period in Scotland were marked by a somewhat different type of eruptions, namely, by numerous more or less isolated volcanoes, many of which were of insignifi-

PLATE IX*a*.



1. Map of Tahiti. "A deeply denuded or water-sculptured" Volcanic Cone.
After J. D. Dana.



2. Marysville Buttes, California (in Contour)—the *disjecta membra* of a formerly lofty and extensive Volcano.

cant dimensions. They appear to have resembled the puys of Auvergne. Some were mere cinder cones from which no lavas came. Others, again, were of more considerable size, and from these not only loose fragmental materials, but flows of lava proceeded. When several such puys were closely associated, their united efforts succeeded in building up broad plateau-like banks, on a smaller scale, however, than the similar volcanic banks of early Carboniferous times. Most of the eruptions now referred to seem, like those of the preceding stage, to have taken place in lagoons and estuaries or in shallow bays of the sea. Now and again, however, the puys were probably subaerial.

The dominant movement of the crust during the growth and decay of these later Carboniferous volcanoes was one of subsidence, so that the puys which erupted in lagoons or upon the floor of the sea were eventually buried under slowly accumulating sheets of sedimentary materials, and in this manner many of them have been preserved. That the eruptions frequently took place under water is shown by the intercalation amongst the tuffs of fossiliferous shales, etc., and now and again of limestones, containing sea-shells and corals. It is improbable, however, that all the eruptions were subaqueous. Doubtless some of the larger puys originating upon the floor of sea or lagoon eventually succeeded in becoming subaerial. Nor is evidence wanting to suggest that some volcanoes erupted on dry land, and after their extinction became clothed with

coniferous trees, the remains of which often occur abundantly in the tuffs associated with the old vents.

Although in certain cases portions of the lavas and fragmental materials ejected from the puys still surround the foci of eruption, yet more usually the cones have completely vanished, and all that remains to mark their sites are the plugs of igneous rock that occupy the "necks" or pipes of eruption.

The relics of these younger puys often form notable features. Fife is especially rich in this respect. The Binn of Burntisland (Plate XI), the Hill of Beath, and the Saline Hills are excellent examples. The Castle Rock of Edinburgh, Binns Hill and Tor Hill in Linlithgowshire, Great Moor, Tinnis Hill, and other similar isolated hills in Liddesdale may also be mentioned.

Volcanic action had ceased before the close of Carboniferous times, but, after a protracted pause, it again manifested itself in the subsequent Permian period.[1] The volcanoes of that period all belonged to the puy-type, and most of them were small Many, indeed, appear to have been mere cinder cones—the products of one eruption. From some,

[1] The Scottish Permian strata, consisting mainly of red sandstones, have only a very limited distribution. They occur chiefly in the valley of the Ayr, and in Nithsdale and Annandale. Owing to the paucity of their organic remains, there is some uncertainty as to their precise stratigraphical position, but they probably were deposited during the later stages of the Permian period, and may even pertain in part to the subsequent Triassic period. They appear to have been accumulated in inland lakes or basins.

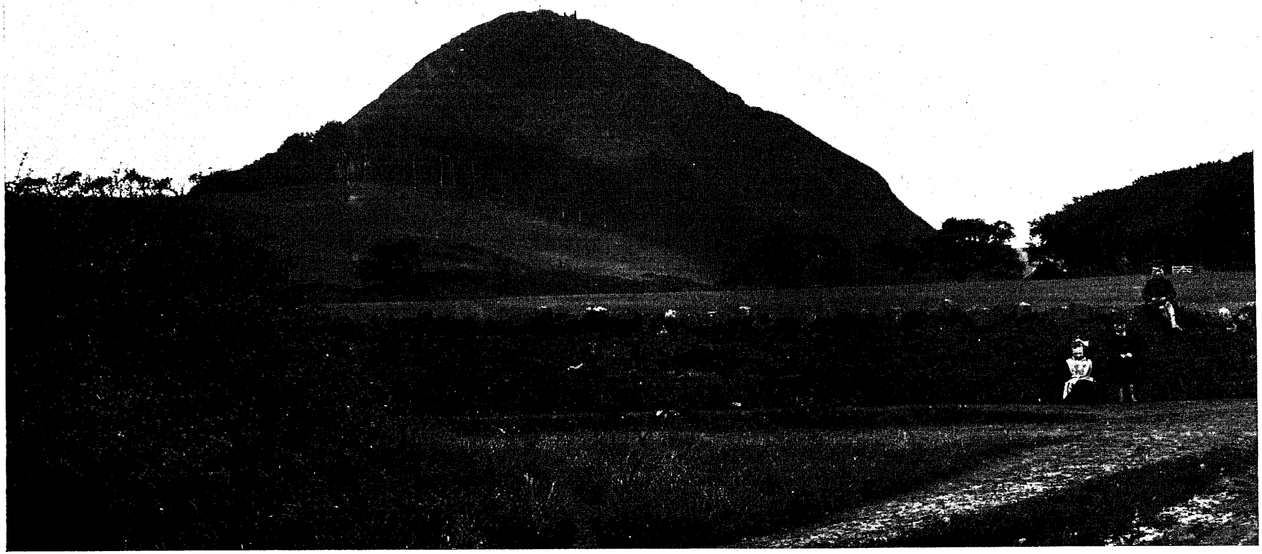
however, not only fragmental materials but lavas were ejected. Frequently these puys are disposed along lines of "faults" or fractures; at other times they do not appear to be connected with such dislocations, but occur scattered about in irregular groups. They are especially numerous in Ayrshire and the east of Fife. As in most cases only the plugged-up "necks" remain, it is often impossible to say whether the puys erupted in water or on dry land. In the valley of the Ayr, however, lavas and tuffs are interstratified with the red sandstones, and the same is the case in Nithsdale; it is quite certain, therefore, that some at least of the Permian eruptions were subaqueous. Bearing in mind that the Permian sedimentary strata were formerly much more extensive, and may well have covered wide areas over which many isolated "necks" are distributed, it is not improbable that these latter may also have erupted within the ancient basins, their lavas and tuffs, and the sandstones with which they may have been interstratified, having been subsequently removed by denudation.

In the east of Fife many old vents occur which have been assigned to the Permian period, although no strata of that age are met with in that region. They closely resemble, however, the corresponding "necks" and dissected cones of Ayrshire and Nithsdale, and like those they are of much later date than the Carboniferous strata they traverse. They often form conspicuous isolated hills, such as Kellie Law

and Largo Law (Plate XII), and numerous examples can be studied upon the shore between Elie and St Monans, where they have been bared and cut into by the sea.

The Scottish "necks" necessarily vary in configuration with the nature of the rock that fills them. When that is basalt or other crystalline igneous rock, we usually have a bold rocky height, rising abruptly or even precipitously above the general level of the neighbourhood, as in the case of the Castle Rock of Edinburgh. Or the "neck" may appear as a more or less prominent conical or pyramidal grassy hill — North Berwick Law being a good example. When the rock of a vent is tuff or agglomerate (*i.e.*, an aggregation of fragmental materials), it generally gives rise to a rounded monticle with smooth slopes, often conspicuous not only by reason of its height, but because of the brightness of its grassy covering, for the disintegrating and decomposing tuff yields a fertile soil. Largo Law and Kellie Law in Fife, and Green Hill near Dalmellington in Ayrshire are good examples. In a great many cases both tuff and crystalline rock occur in the same "neck," and give variety to the configuration of the hill by the different way in which they have "weathered"—the tuff yielding soft curving outlines, while the crystalline rock often projects boldly in rough knolls and broken crags or precipices. Of this type of hill Arthur Seat at Edinburgh is an excellent example.

PLATE X.



NORTH BERWICK LAW, HADDINGTONSHIRE. [Neck of a Carboniferous Volcano plugged up with Trachyte.]

Photo, H.M. Geological Survey.

PLATE XI.

THE BINN, BURNTISLAND, FIFE.

[Neck of a Carboniferous Volcano, filled up with Agglomerate, which is traversed by Dykes and Veins of Basalt.]

Photo, H.M. Geological Survey.

[*Between pages* 40 *and* 41.

Geysers

Before leaving the subject of volcanic hills and mountains, brief reference may be made to the action of thermal waters, and more particularly of those intermittent eruptive springs and fountains of hot water and steam called geysers, which occur in many volcanic regions. The water is more or less abundantly charged with mineral matter in solution, consisting mainly of silica or of carbonate of lime as the case may be. The geysers of Iceland were the first to arrest attention, but they are surpassed in importance by the much more numerous hot-water springs and fountains of the Yellowstone Park (U.S.A.). In that region some of the geysers spout water to a height of 100 feet or even 200 feet (see Plate XIII). When a fountain erupts on level ground, it very slowly builds up a low depressed mound or a more abrupt cone of mineral matter. The deposition of the mineral matter is due partly to the cooling and evaporation of the water as it flows outwards, and partly to the action of minute thread-like algæ which secrete silica from the hot water, forming a slimy mass in which they flourish. As the silica hardens internally they die there, but new crops continue to flourish on the outside, and thus continually add to the growing mass. The sinter formed in this way is often brilliantly coloured, but the rich colours fade away when the geyser ceases to work and the algæ die out.

Geyser mounds are of relatively insignificant

dimensions, seldom exceeding thirty feet in height, and being usually very much lower. When hot-water fountains erupt upon a slope they tend to form a series of terraces rather than mounds and cones.

The water of the geysers from which silica and lime are deposited is usually clear. Occasionally, however, a geyser discharges very muddy water, the mud derived no doubt from the disintegration and decomposition of the underlying rocks. In some regions of active or recently extinct volcanoes, fountains and pools of boiling and spluttering mud are of common occurrence. Occasionally the mud is violently discharged, and falling back around the point of eruption, gradually builds up a cone with a crater, resembling in this respect a miniature volcano. None of these cones, however, rise higher than a few feet.

Air Volcanoes

Here a word may be added as to certain mud cones known as *maccalubas*, *salses*, or *air volcanoes*, although they are not truly of volcanic origin. They are due, in fact, to chemical processes taking place at some little depth, and evolving various gases more or less abundantly. These force to the surface quantities of liquid mud, which, according to the pressure exerted by the escaping gases, either oozes out in a tranquil manner, or is ejected with some violence. The cones of mud resulting from this action closely simulate those of volcanic regions; the motive power of the latter, however, is steam.

Usually "air volcanoes" are mere hummocks, but occasionally they may attain thirty yards or more in height. It need hardly be added that geyser cones and mud cones of all kinds are evanescent features. When the motive power, whether it be hot water and steam or gas, ceases to act, the cones begin to crumble away. The domes of dried sinter crack and break up into a shaly friable mass, and are soon reduced by rain and wind, and desiccated mud cones are even more readily destroyed by the same agents.

CHAPTER III

ORIGINAL OR TECTONIC MOUNTAINS—*continued*

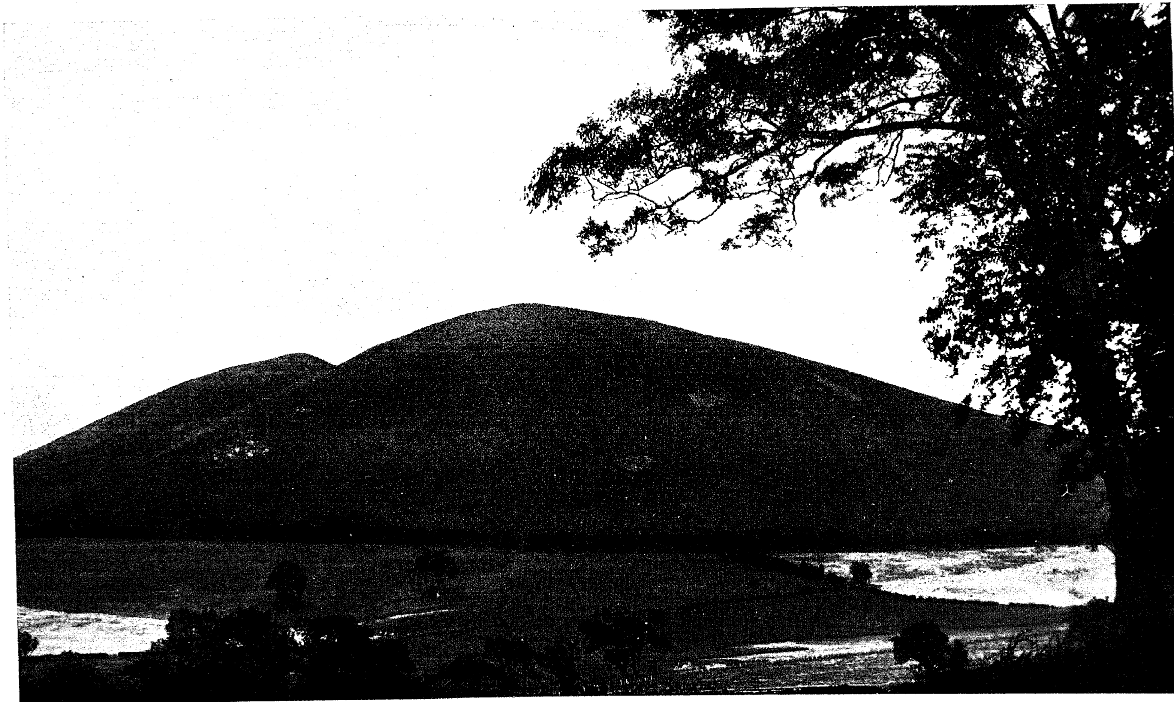
Accumulation Mountains of Epigene Origin: Glacial Hills—Terminal Moraines; Drums or Drumlins; Eskers. Æolian Hills or Dunes—Desert Sandhills; Coast Sandhills; Sandstones of Æolian Origin. Modification of Accumulation Mountains.

EPIGENE TYPES

WE may now take a brief glance at certain heights of the land which have been heaped up by other than volcanic agency. The forms we are about to pass in review owe their origin to the transport and accumulation of superficial materials; they are due, in short, to epigene or surface action alone. None are of sufficient importance to be called mountains, most epigene heights being mere mounds and hillocks. Nevertheless they are not infrequently rendered prominent by reason of their abundance, and are very characteristic of many extensive regions. We shall describe them under these two heads—*Glacial hills* and *Æolian hills.*

Glacial Hills

Alpine glaciers, as everyone knows, are usually more or less abundantly besprinkled with rock-riven debris, showered upon them from the mountains that



LARGO LAW, FIFE. [A dissected Volcanic Cone, probably of Permian age; composed chiefly of Tuff, traversed by Dykes and Veins of Basalt, and showing a bed of Basalt which may have flowed out at the surface.]

Photo, H.M. Geological Survey.

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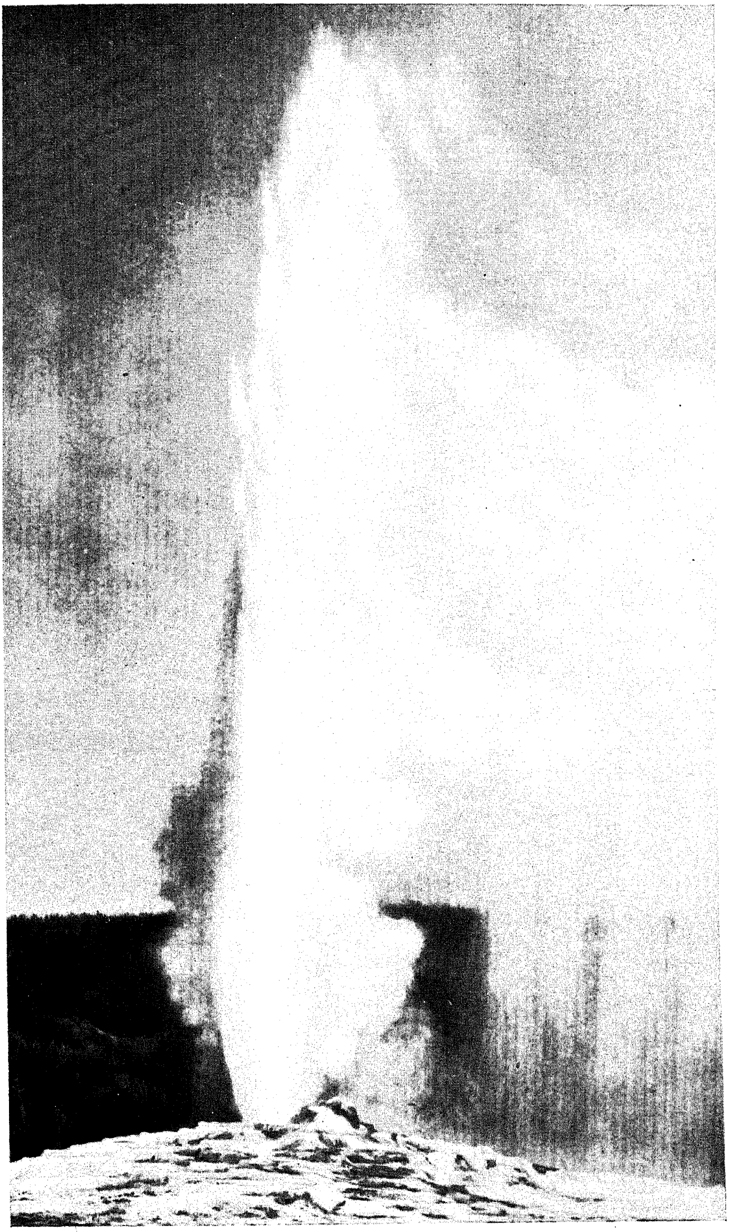
overlook them. The debris gathers chiefly upon their flanks, where it constitutes what are known as *lateral moraines*. When two or more glaciers unite to form one large ice-flow, some of the lateral moraines necessarily coalesce and so become *medial moraines*. In this way the surface of a considerable trunk glacier is marked longitudinally by a less or greater number of parallel ridges, composed of angular rock-fragments of all shapes and sizes, from huge blocks down to finely comminuted debris. These superficial accumulations eventually reach the front of the slowly moving glacier, where they topple over to form *terminal moraines*. Should the ice-front maintain its position for a considerable time, the moraines, constantly receiving supplies, must continue to grow. But glaciers are well known to have their periods of advance and retreat. When the ice advances the terminal moraines are pushed forward, and should their bulk be very great they may be to some extent overridden. When, on the other hand, the glacier recedes, the moraines are left stranded to form mounds or ridges, which will be more or less prominent according as the ice-front has remained for a longer or shorter time in the same place. Thus each lengthened pause during the retreat of an ice-front is indicated by a belt of moraines that stretches across the valley from side to side, save for the broad gap or passage which is kept open by the river that always flows out from underneath the snout of a glacier.

The presence of such terminal moraines at low levels in the valleys of the Alps, and even on the

plains opposite their mouths, is one of many other proofs that those mountains formerly nourished far more important glaciers than they do in our day. Although the moraines are gigantic as compared with any now forming in the Alps, they are after all mere hillocks and ridges, dwarfed into insignificance by the great mountains amongst which they lie. Nevertheless when they occur outside the valleys they acquire some importance. In northern Italy, for example, the moraines at the mouth of the Dora Baltea are almost mountainous in their dimensions, forming long-extended ramparts that rise to a height of over 800 feet above the adjacent plains. Even more impressive, by reason of the immense areas they occupy, are the multitudinous wreaths and sheets of rolling banks, mounds, knolls, hills, and ridges, with their innumerable associated lakelets and pools, that stretch far out upon the Alpine forelands in Bavaria, Swabia, Switzerland, and eastern France.

The moraines occurring within the mountain-valleys of the Alps consist largely of unassorted rock-rubbish, commingled with which, however, there is usually some gravel and sand, meagre or abundant as the case may be. In the moraines of the forelands, on the other hand, gravel and sand are most prevalent, although angular blocks, boulders, and rude rock-debris are seldom absent, and sometimes even preponderate.

Terminal moraines of one kind or another are commonly associated with all the mountainous tracts of middle and southern Europe. They are likewise



OLD FAITHFUL GEYSER, YELLOWSTONE PARK, WYOMING, U.S.A.

Photo. Detroit Pub. Co.

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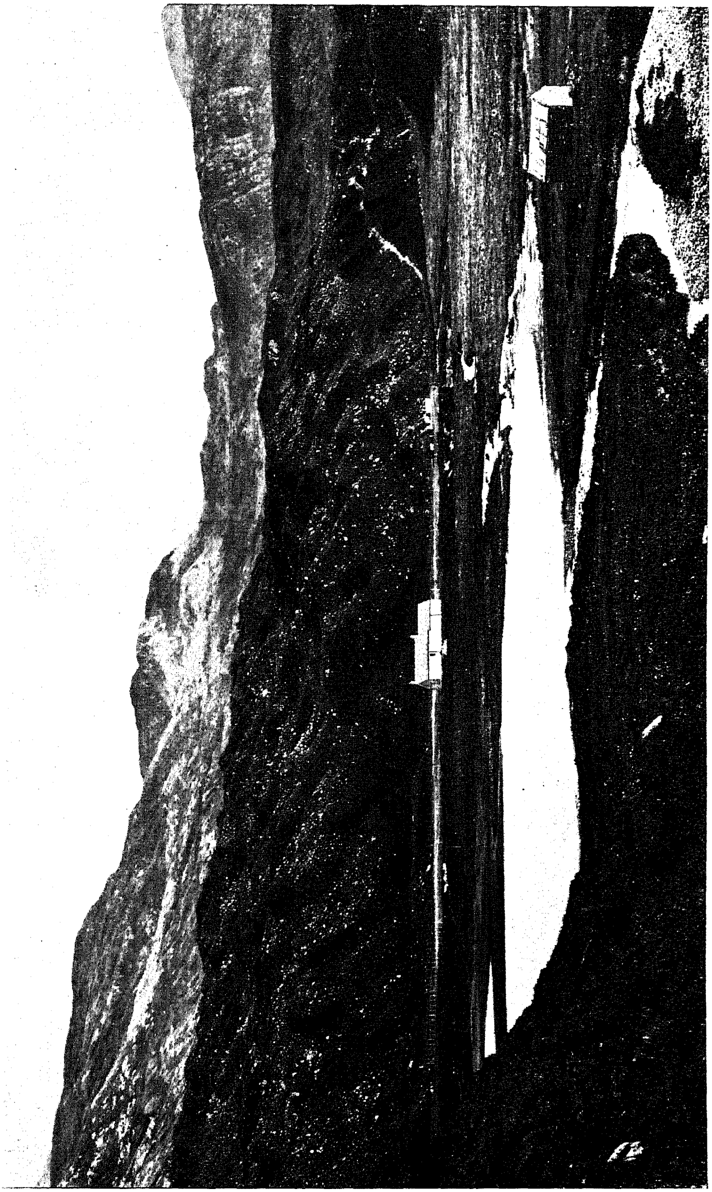
well developed in Norway and Sweden, and the hilly tracts of our own islands. The general appearance of the hummocky moraines of the Highlands is well illustrated in Plate XIV, while a good example of a solitary morainic hill is shown in Plate XIV*a*, I. But the most notable terminal moraines in northern Europe are those of the several ice-sheets that covered that region at various stages of the Glacial period, and were doubtless contemporaneous with the similar successive advances of the great Alpine glaciers. Each advance and retreat of the northern ice-sheets left the low grounds overspread with much fragmental material, the most conspicuous formations being as usual gravelly moraines. For various reasons, the terminal moraines of the earlier and more extensive *mers de glace* are neither so abundant nor so prominent as those which were laid down by the latest and least considerable ice-flow. During the epoch of maximum glaciation the whole of north and north-west Europe, including the British Islands, was overflowed by a *mer de glace*, which advanced south as far as the Thames valley and the foot of the Harz and the Erz Mountains. Only a few of the higher hill-tops of our islands, and the summits of the loftier Scandinavian mountains rose above that wide sea of ice, the surface of which, therefore, could not be sprinkled with much superficial morainic debris. Hence the terminal moraines accumulated at the ice-front show a relatively small proportion of rude rock-rubbish and, like the morainic heaps of the Alpine forelands, are made up largely of gravel and sand. Moreover, so long a

time has elapsed since the time of their formation, that they have experienced considerable denudation. For these and other reasons which need not be discussed here, the terminal moraines of the more extensive ice-sheets are much less prominent objects than those laid down in front of the latest and smallest of the Scandinavian *mers de glace*. But relatively inconsiderable as that youngest ice-sheet was, it nevertheless practically covered the Scandinavian peninsula and Finland. On the west it descended to the margin of the North Sea, filling up most of the great fiords; on the east it buried Sweden, occupied the Gulf of Bothnia, and overwhelmed Finland and a large part of western and north-western Russia. It formed, in short, a gigantic glacier that completely filled the basin of the Baltic, and encroached far upon the low-lying lands of East and West Prussia, Pomerania, Mecklenburg, Schleswig-Holstein, and Denmark.

The terminal moraines of that enormous glacier are cônspicuous in all these lands, where they acquire an importance which they could not have in a country of bolder relief. They constitute, indeed, the most extensive *paysage morainique* of Europe—a broad region crowded with innumerable winding and interosculating ranges of hummocky ramparts and ridges, and vast assemblages of rounded conical knolls, mounds, and hills, the hollows amongst which hold lakes and lakelets, bogs and morasses innumerable. Similar gravelly moraines are common in our own islands. In Scotland, for example, they are often



Photo, H.M. Geological Survey.

LOCHAN AN IASGAICH, ROSS-SHIRE.

[Showing in middle distance numerous hummocky moraines.]

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(1) MORAINES, CALDER VALLEY, KINGUSSIE, INVERNESS-SHIRE.
Photo, Miss Newbigin, D.Sc.

(2) A SWEDISH OS OR ESKER.
Salisbury's "Physiography."

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well developed in the low grounds opposite the mouths of our Highland valleys, as in Strathmore, and they occur again and again in like positions upon the low-lying tracts that extend outwards from the dales of the Southern Uplands, as in the neighbourhood of Carstairs and Carnwath in the valley of the Clyde. Very characteristic are these Scottish examples, but they are of course on a much smaller scale than the terminal moraines of the great Baltic glacier.

The *paysage morainique* of northern Europe, however, is far surpassed by that of North America. Not only are notable terminal moraines abundantly developed amongst the Rocky Mountains and other elevated tracts, which, during the Ice Age, nourished an infinite number of glaciers, large and small, but they beset large areas in the northern States of the Union and in Canada. Practically all the region stretching for many miles south of the great lakes and extending from northern New Jersey and Pennsylvania west to the foot of the Rockies is one great *paysage morainique*, where the glacial phenomena characteristic of the low grounds of northern Europe are repeated on a grander scale.

Besides such conspicuous objects as terminal moraines, certain other features of glacial origin call for brief notice. Throughout those parts of our continent formerly overflowed by extensive *mers de glace*, the ground is often closely swathed in thick sheets of a stony clay—the "boulder-clay" of geologists. The ground so covered may show no prominent outlines, but merely rise and fall in long gentle undula-

tions. Now and again, however, the undulations become more pronounced; the stony clay forming well-marked parallel ridges and prominent banks, or a series of short lenticular mounds, hummocks, and hills, all drawn out in some particular direction. These features are for the most part original, and not the result of subsequent erosion. The stony clay is the product of glacial grinding, and accumulated underneath the *mers de glace*, as a bottom-moraine, the trend of the ridges and mounds indicating the direction of ice-flow.

But more striking than these subglacial "drums" or "drumlins," as they are called, are the long winding ridges of gravel, or of gravel and sand, known as "eskers" in this country and as osar (åsar) in Sweden, where they are typically displayed (Plate XIV*a*, 2). These osar rise abruptly above the average surface of the ground from a height of less than 50 feet to 100 feet or even 180 feet. When a ridge is composed of coarse gravel its sides slope at angles of 25° to 30°; but the inclination diminishes usually as the ingredients become finer-grained, so that in sandy osar it may not exceed 20° or 15°. Often beginning in the interior of the country these great natural embankments follow the valleys down to the low coast-land, across which they pass as well-defined ridges to the Baltic, after a course of sometimes 200 English miles. A series of these osar expressed upon a map bears a striking resemblance to river-courses large and small, each main os being joined by more or less numerous tributaries (see Fig. 16). A glance

at the map of the osar in the basin of Lake Mälar will show that at low levels they are tolerably independent of the configuration of the surface. These remarkable ridges appear to mark the courses of

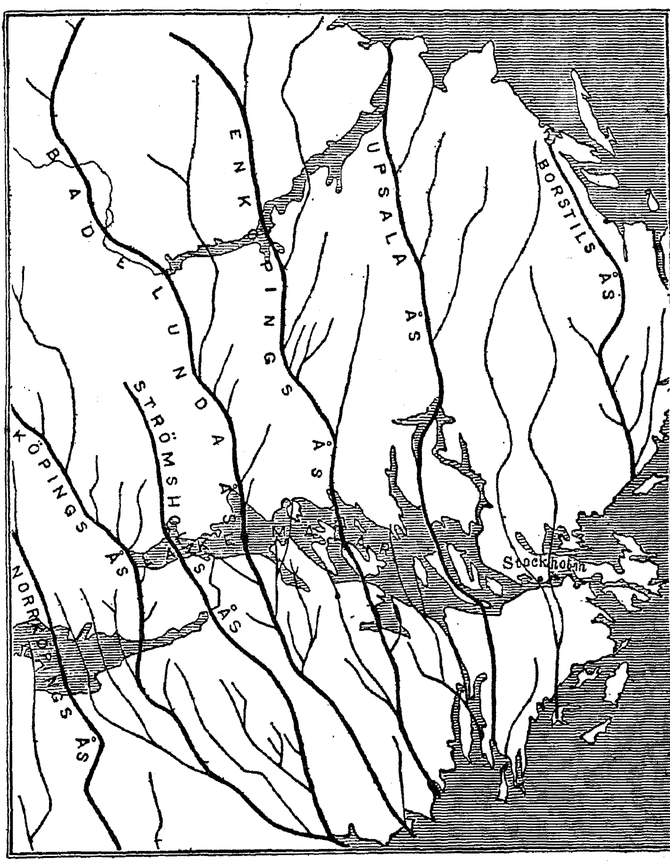

FIG. 16.—Map of Osar in Basin of Lake Mälar. (After A. Erdmann.)

rivers that flowed underneath the last *mer de glace*, or great Baltic glacier which overwhelmed that part of Sweden. At the time of their formation the *mer de glace* had probably ceased to flow and was under-

going more or less rapid dissolution. Water falling copiously from above, through moulins and crevasses, descended to the bottom of the ice-sheet, where it licked out a series of tunnels, through which torrents and rivers made their way, keeping to the valleys in the interior of the land, but, when the low grounds were reached, following a more or less independent course to the basin of the Baltic. Similar ridges occur more or less commonly in many other formerly glaciated lowlands, as in Scotland and Ireland, the eskers of Ireland being quite as marked a feature of the central plain of that country as its abundant drumlins.

Æolian Hills

The only other hills of accumulation that call for special notice here, are those heaps of sand which are piled up by the action of the wind and known as dunes. The most characteristic hills of the kind occur in dry desiccated tracts, where they often cover enormous areas. In ground-plan a typical desert-dune is crescentic or sickle-shaped. Any abrupt obstacle in the path of the wind, however insignificant it may be, such as a bush, a tuft of grass, a stone, a slight inequality in the surface of the ground, or even the wind itself coming in gusts, may cause a dune to form. The sand arrested in front of an obstacle is gradually piled up against it as a gently-inclined bank, which continues to increase in width as the sand sweeps round to right and left. Eventually the obstacle is overtopped, the sand dropping down and

accumulating in the lee as a relatively steep cliff-like bank. As the dune grows in height its wings continue to increase in width, and curve round so as to enclose a sheltered bay in the rear. Endless modifications of this crescent type are met with, some dunes being heart-shaped in ground-plan, while others have the form of a horseshoe or a half-moon (Fig. 17, p. 54).

The height attained by a dune is determined by the strength of the wind, the supply of sand, and probably in some measure also by the size of the sand-grains. As the sand travels up the gentle windward slope and comes to rest in the lee, the dune itself necessarily moves forward in the direction of the wind. Dunes of the kind described may occur sporadically scattered over a sandy waste, sometimes as single isolated hills, at other times in groups, or a number may coalesce to form a range or chain. Elsewhere they may crowd together and cover an enormous area—a far-extended sea of hills. In such a case, should the wind blow persistently in one direction, the hills are usually drawn out in long parallel ranges running in the same direction. Even under those conditions traces of the typical crescentic form now and again appear. But in deserts where the winds blow from different quarters little or no parallel arrangement of the dunes may be seen, while the type-form, if never quite absent, is generally inconspicuous.

While isolated desert dunes range in height from less than 20 feet to 100 feet or thereabout, such

heights are often exceeded by the long parallel ranges

FIG. 17.—Ground-plan of Desert Dunes: Buchara, Turkestan. (After J. Walther.)

of sandhills, some of which are occasionally as high as 300 feet, or even 600 feet.

PLATE XV.

SANDHILLS, CULBIN, MORAYSHIRE.

[In the background an advancing dune. Direction of wind shown by tails of sand behind tufts of "bent" grass, and by rippled surface in foreground.]

Photo, H.M. Geological Survey.

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Among the more notable dune-lands of the Old World are those of north Africa, Arabia, Persia, Turkestan, Gobi, and north-west India. At one time it was the general belief that great sand-wastes, such as the Sahara, were simply portions of the sea-floor which had been elevated in geologically recent times. It is now recognised, however, that the sands owe their origin to the action known as "insolation and deflation." In warm desiccated regions, which are practically devoid of vegetation, the superficial portions of the naked rocks, exposed to the blaze of the sun, expand during the day and again contract at night. As the diurnal range of temperature is great, the effects of this alternate heating and cooling are very marked. The rocks are cracked and shattered to a depth of several inches; the surfaces frequently peel off, and are rapidly disintegrated and pulverised. Wind next catches up the loose material and sweeps it away, leaving fresh surfaces exposed to the same destructive action. Further, the grit and sand carried off by the wind are employed in grinding and reducing the rocks against or over which they are swept. In this manner cliffs and prominent rocks are not only curiously etched, fretted, furrowed, and honeycombed, but, as the drifting sand seldom rises more than a few feet into the air, they are eventually undermined by its scouring action. Hence larger and smaller masses, losing support, ever and anon fall to the ground, where they become in like manner subject to attrition and disintegration, until they are finally

removed in the form of grit, sand, and dust. So effective is the action of sun and wind that the whole surface of a rainless region is gradually denuded and lowered, the loose materials continually travelling onwards to the borders of the desert. The sands of continental dune-lands, therefore, have no necessary connection with abandoned sea-floors. It is true that within certain desert areas there exist lakes and inland seas that are gradually drying up. In the great Desert of Gobi, for example, lakes occur which have obviously at one time been considerably more extensive. So again in the Aralo-Caspian depression, abundant sandhills are scattered over wide areas, which were certainly under water at quite a recent geological date. Within such tracts, therefore, after the water had disappeared, much loose sand was doubtless already prepared for the direct action of the wind. But in the case of extensive deserts, such as those of north Africa, central Arabia, etc., the sand has been derived almost wholly from the subaerial disintegration of rocks.

In many regions, however, as in Poland and north Germany, we encounter broad stretches of loose sand, which have had quite a different origin. They are, in short, fluvio-glacial accumulations, laid down by the abundant waters escaping from the melting ice-sheets of the Glacial period. Subsequently coming under the dominion of the winds, they have been blown about and heaped into dunes, now largely overgrown with heath, but in some

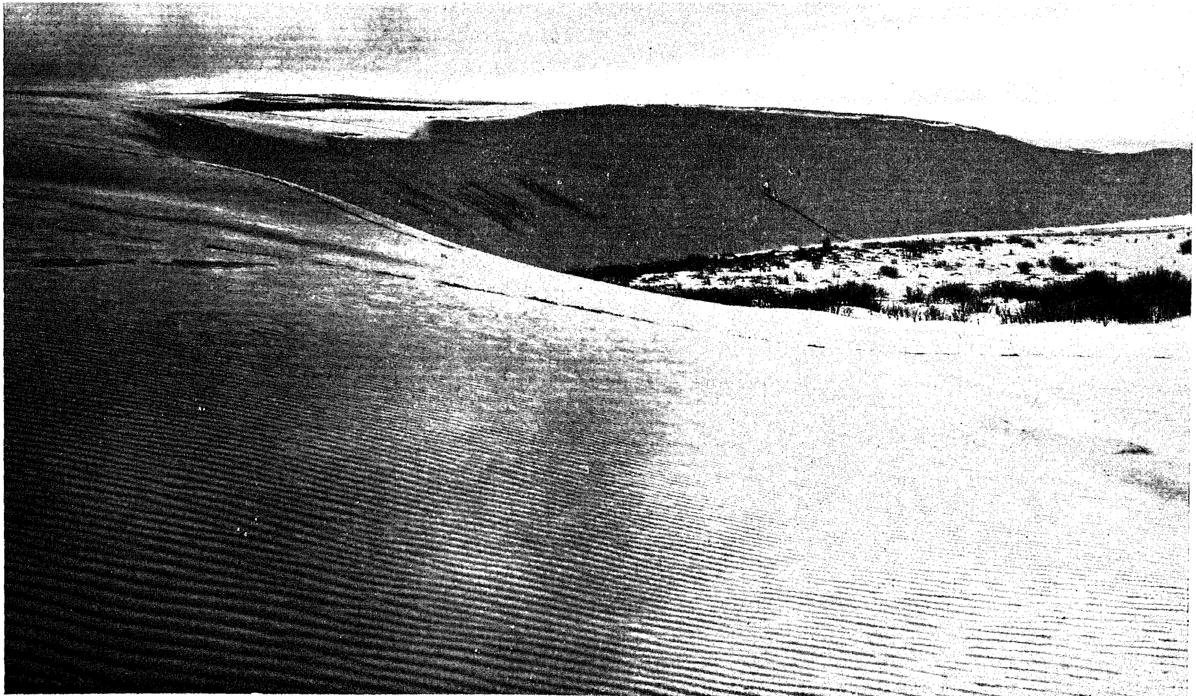
PLATE XVI.

MAVISTON SANDHILLS, MORAYSHIRE.

[Advancing sand overwhelming a plantation of Scots fir. Note the flutings at top of slope, due to arrest of sand by tops of buried trees.]

Photo, H.M. Geological Survey.

PLATE XVII.



SANDHILLS, CULBIN, MORAYSHIRE.

[On right centre an old land-surface swept bare of sand : direction of wind almost directly towards observer, as shown by the steep bank with cornice atop and the ripples in foreground.]

Photo, H.M. Geological Survey.

[*Between pages 56 and 57.*

places (as in Russian Poland), naked as the sand-hills of the Libyan desert.

The sand of coastal dunes is in like manner the product of aqueous action, thrown up by the waves on the beaches of seas and large freshwater lakes, whence it is blown inland, and either spread out in extensive sheets with a broadly undulating surface, or heaped up into a series of more abrupt rounded hummocky ridges, running parallel with the coast. Not infrequently no such parallel arrangement is seen, the dunes appearing as a tumultuous assemblage of conical hillocks and short curving banks and ramparts. One of the most notable areas of coastal dunes in this country is that of Culbin, on the southern borders of the Moray Firth. These sands cover an area of more than 9000 acres, of what was at one time a fertile and highly cultivated region. Plates XV-XVIII will give the reader a better idea of the general aspect of this dreary desert tract than any mere verbal description. Plates XVII and XVIII are especially interesting, as showing how dunes after overwhelming a tract may gradually move on and leave the same tract exposed.

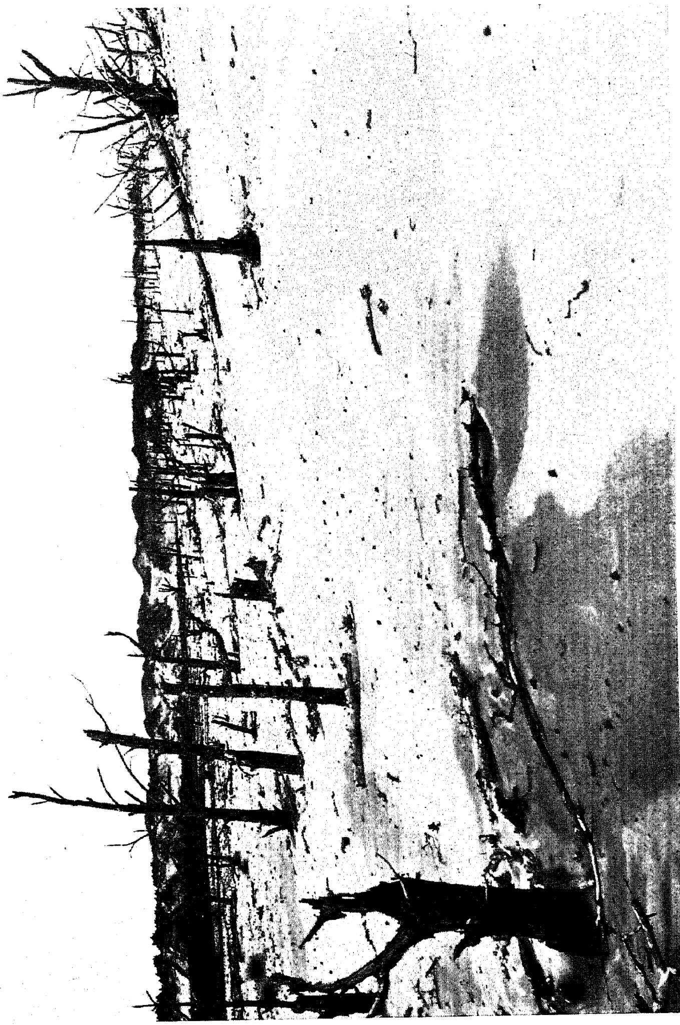
Coast-dunes, like those of deserts, vary in height from a few yards up to 50 feet or more. Exceptionally they may reach 200 or 300 feet; while heights of even 600 feet have been recorded, as on the coast of Tunis, where in summer north winds prevail. When the dominant wind blows towards the land, the dunes, as might have been expected, are usually

higher than on coasts where the winds are very variable. In the region of the monsoons, for instance, the wind blows alternately from land and sea, and high dunes are rarely formed; while in places where the prevalent wind is from the land, as in Provence, sandhills are either wanting or quite insignificant.

Dunes are best developed upon gently shelving shores, where considerable tracts of beach are laid bare at low water. They are of common occurrence under such conditions in our own islands, as at Culbin, where the sand thrown up by the sea is in large measure derived from submerged fluvio-glacial accumulations of the same origin as the blown sands of Poland and north Germany. The abundant dunes of the Danish coast-lands, and those of the Low Countries, have in all probability a similar tale to tell. In non-glaciated regions, on the other hand, the sand of coast-dunes has obviously in many cases been carried down to the sea by rivers; while in other cases it is largely derived from unconsolidated deposits of Tertiary or more recent age, that cover the sea-floor. Much sand, however, results from the erosive action of waves and breakers on rocky coasts, and is drifted by tidal currents into shallow bays, whence it is washed ashore upon low shelving coasts, to be heaped up by the wind.

Dunes differ from all other hills of accumulation in one very obvious particular: as they grow they move—"like clouds they shape themselves and go." They are comparable to the banks of sand and gravel that gather on the beds of large rivers—"for ever

PLATE XVIII.



SANDHILLS, MAVISTON, MORAYSHIRE.

[Pine Forest formerly overwhelmed by sand, now re-exposed by further advance of the sand.]

Photo, H.M. Geological Survey.

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changing and yet still the same." So long as desert conditions persist, so long as waves throw up sand upon a shelving shore, dunes will continue to form. In desert regions they constantly advance in the direction of the prevalent wind, until it may be they reach some lake or river, or the sea itself. There the sand is arrested and deposited or carried away. Coast-dunes, on the other hand, steal inland, where eventually the movement may be gradually impeded by vegetation.

But although dunes seem to be largely independent of the various agents of erosion to which all other hills and mountains of accumulation sooner or later must succumb, they are yet not so immune as they would seem to be. We know that again and again desert conditions have prevailed in regions which subsequently enjoyed a genial climate, and nourished an abundant vegetation. The deserts vanished and were replaced by well-watered lands. Great salt lakes and sandy deserts, for example, characterised what are now the temperate latitudes of middle Europe during Permian and Triassic times. But, owing to changed climatic conditions, the blowing sands became fixed, and were eventually consolidated into sandstones, after which, it is needless to say, they were as liable to denudation as any other kind of formation—igneous, aqueous, or glacial.

We have now passed in review the several types of mountains which owe their origin to the accumulation or heaping-up of materials at the surface. However much these may differ otherwise, they yet all

agree in one fundamental particular—their external form is an expression of their internal structure. With very few exceptions their growth is exogenous; they increase by additions to the outside. Only in the case of a small number of relatively unimportant volcanoes does increase take place by internal growth, so as to produce an endogenous structure.

Even during the period of growth, mountains of accumulation are subject to modification by epigene action of one kind or another, the constant tendency of which is to reduce the heights of the land to one general level. Consequently when a mountain ceases to grow, the process of decay goes on without interruption, the mountain becomes more and more dilapidated, until finally it may be utterly destroyed. The rate of decay varies indefinitely, according to the nature and arrangement of the materials of which the mountain is built up, and the physical conditions that surround it; but all are subject to the same universal law, even mobile and mutable dunes eventually become fixed, and follow the fate of their apparently stable but nevertheless evanescent congeners.

CHAPTER IV

ORIGINAL OR TECTONIC MOUNTAINS—*continued*

Deformation Mountains: Theories of their Origin; Views held up to End of Eighteenth Century; Opinions of Hutton and Playfair, of Elie de Beaumont and Lyell. Folded Mountains: Their General Character; Varieties of Folds; Slaty Cleavage; Foliation or Schistosity; Metamorphism of Highly-folded Rocks. Direction of Crust Compression —Overfolds and Horizontal Displacements.

Deformation Mountains

We come now to study the second great class of tectonic mountains, those, namely, which owe their origin to subterranean action, to deformation of the earth's crust, whether by folding or by dislocation and displacement. Nearly all the more prominent ranges and chains of the globe come under this category. It used to be a prevalent belief that these mountains were primitive; or, in other words, original protuberances of the earth's surface. This was the view held by Leibnitz in 1749, and maintained by Buffon in 1790. Long before that time, however, Steno, a Dane, formerly Professor of Anatomy at Padua, published (in 1669) a remarkable treatise wherein he tried to show that the existing inequalities of the earth's surface were obviously connected

with disruptions of the crust. He certainly did not suppose that mountains were primitive, and similar views were subsequently entertained by Lazzaro Moro in Italy (1740), and by John Michell in England (1760). According to these observers earthquakes and volcanic action must be invoked to explain the phenomena. But the old belief in the primitive origin of mountains died hard, many writers of the eighteenth century still maintaining that view, while at the same time admitting that some mountains were truly volcanic.

Before the century closed, however, the truth had dawned on Dr James Hutton of Edinburgh, whose sagacious observations and original conceptions were supported and extended by his friends and disciples, Professor John Playfair and Sir James Hall. These able men recognised that mountains were composed of flexed, convoluted, and fractured rock-masses, and hence they maintained that such structures were indisputable proof that the crust itself had been upheaved, a conclusion that soon gained general acceptance. Both Hutton and Playfair believed that the rock structures referred to were the result of violent disturbances, but they did not go so far as to infer that all earth movements were of this nature. Playfair, indeed, when speaking of the present lands, says quite clearly that they "have been raised up from the bottom of the sea by a process that should seem in general to have been gradual and slow." And such continued to be the opinion for many years, two kinds of crustal movement being recognised, one

violent and sudden, as in the formation of mountains, the other gradual and protracted, as in the elevation and depression of broad land surfaces.

From Hutton's day down to nearly the middle of last century, it was commonly supposed that mountains had been elevated by "a force directed from below upwards." And of all the forces in nature none seemed to Playfair "so capable of the effect we would ascribe to it as the expansive power of heat." His friend, Sir James Hall, however, had shown experimentally that rock-folds had most probably been caused by horizontal thrusts, and the source of the lateral compression, according to him, was "the forcible intrusion of granite." Granite or other molten mass, it was supposed, coming up from below, had invaded an area of originally horizontal strata, and by thrusting the beds aside had flexed and folded them. This was the germ of the "plutonic theory" that subsequently came into vogue, according to which mountains owed their origin to the uprising of those enormous masses of granite that so frequently crop out along the axis, and seem to form the core of many a mountain range.

Elie de Beaumont, the famous French geologist, although far in advance of most of his contemporaries as a keen observer and original thinker, nevertheless continued to believe that mountains owed their origin to sudden and violent movements of the crust. He conceived that during the cooling and contraction of the earth's interior, the external crust did not gradually sink so as to keep continually in touch with the

slowly shrinking nucleus. For long periods of time it sustained itself, and thus became partially separated from the molten interior. Eventually, however, sudden collapse took place; and, since the crust had to accommodate itself to a smaller space, much crushing, compression, and consequent folding of strata ensued, while here and there relief was found in a vertical direction by the violent upheaval of long ranges and chains. These bold conceptions met with considerable acceptance for a time, and were believed to explain the appearance, along the axis of a mountain chain, of granite and other crystalline rocks in a more satisfactory manner than the old plutonic theory. It was inferred that the central axis of a chain coincided with a great vertical fracture, that the crust, yielding to tension, had cracked across, the free ends of the sundered rock-masses rising up vertically along the line of disruption, while molten matter was intruded between them.

Sir Charles Lyell, the great apostle of uniformitarianism, stoutly opposed Elie de Beaumont's conclusions, and insisted that there was no evidence to show that such paroxysmal or catastrophic movements of the crust had ever occurred. He thought that "the gradual fusion of rocks, and the expansive power of heat exerted for ages, as well as the subsequent contraction of the same during slow refrigeration, might perhaps account for the origin of mountain chains." Referring to mountains as relatively insignificant surface features of the globe, "far less important, proportionately speaking, than

the inequalities on the surface of an egg-shell, which to the eye appears smooth," Lyell concluded that "a centripetal force affecting the whole planet as it cools, seems a mightier cause than is required to produce wrinkles of such insignificant size." But beyond this and some other vague suggestions that admirable writer did not offer any particular explanation of the origin of mountain structure. He recognised, indeed, that convoluted strata are evidence of compression, and endeavoured to account for the source of the pressure in various ways. Referring to the great earthquake of 1822, which resulted in the permanent elevation of the coast of Chili for a few feet, he remarks that the power which could do this would suffice to produce any amount of rock-folding, if its direction instead of being vertical happened to be oblique or horizontal, and if the rocks were "subjected for a sufficient number of times to the repeated action of the same force," which, in this case, he thought was volcanic. But he offered no suggestion as to how the desired oblique or lateral thrust could be brought about. Another cause of rock-folding he found in movements of depression. The subsidence of the crust for hundreds or thousands of feet would result, he conceived, in the flexing of strata and the packing of the same into smaller space. Other possible causes of lateral pressure were suggested, but none of these seems to have commended itself to subsequent investigators as an important factor in mountain-making.

Little progress could be made towards a satisfactory theory until the geological structure or architecture of individual mountain chains had been studied with precision. Many observations and descriptions of the folded rocks of the Alps and other regions had been recorded, more especially by that pioneer student of mountain structure, De Saussure; but for half a century after the appearance of his famous *Voyages dans les Alpes* (1779), geology could still present no clear conception of a mountain range as an organic unity. Although Thurmann's researches in the Jura Mountains (1832), and those of De la Beche in Cornwall, Devon, and West Somerset (1839) had exhibited the structure characteristic of true mountains of upheaval, it was not until the appearance in 1843 of the well-known essay by Professors W. B. and H. D. Rogers on the physical structure of the Appalachians, that geologists generally began to realise what is meant by the architecture of mountains of elevation. Thanks to the labours of these brilliant observers and their many successors, we are no longer in doubt as to the part played by compression in the formation of mountain chains.

Before dealing with the present position of the question, however, it may be well to follow for a little another line of investigation intimately connected with the subject of mountain structure and its origin. The history of a mountain range naturally involves that of its valleys. Those who thought mountains were primitive had naturally no doubt about the

valleys—they were primitive likewise. As Hutton was among the earliest clearly to perceive that mountains are uplifts of the crust, so he was the first to show how these elevations have been modelled and sculptured by erosion. "The mountains," he said, "have been formed by the hollowing out of the valleys, and the valleys have been hollowed out by the attrition of hard materials coming from the mountains." His disciple, Playfair, pictures the original upheaval as an immense mass of rock, naked and unshapely, and incomparably greater than all that now remains. "The operation of rains and torrents," he remarks, "modified by the hardness and tenacity of the rock, has worked the whole into its present form; has hollowed out the valleys, and gradually detached the mountains from the general mass, cutting down their sides into steep precipices at one place, and smoothing them into gentle declivities at another."

The contemporaries and immediate successors of those advanced thinkers did not agree with them that subaerial erosion and denudation had played so conspicuous a part in the history of mountains. On the contrary, the views prevalent in the earlier years of last century were those expounded by Elie de Beaumont, according to whom the multitudinous gorges and valleys of a mountain range came into existence contemporaneously with the range itself; in short, they were simply rents and chasms opened at the time of the upheaval. Such were the opinions in vogue when Lyell's *Principles of Geology* appeared.

In this famous work the author, while successfully attacking the catastrophic views advocated by De Beaumont, did not realise the significance of subaerial action so fully and clearly as his predecessors, Hutton and Playfair had done. He insisted, it is true, that "a very large part of the inequalities now existing on the earth's surface are due to fluviatile action," but he thought that "the principal valleys in almost every great hydrographical basin in the world are of a shape and magnitude which imply that they have been due to other causes besides the mere excavating power of rivers." Rejecting the wild notions of his contemporaries that denudation had been effected mainly by sudden debacles, or by vast waves raised by the instantaneous upthrow of continents or of mountain chains out of the sea, he maintained that the chief share in the work of eroding and reducing a land-surface must be assigned to the waves and breakers during protracted movements of elevation and depression. These views, admirably expounded as they were, prevailed for some time, and "ancient sea-margins" were detected by Lyell's disciples almost everywhere; but as observations extended, geologists began to realise that the sea had played a much less important rôle than that assigned to it by their teacher. They gradually returned, in fact, to the position held so long ago by Hutton and Playfair; and even Lyell himself, in the later editions of his works, came to modify his estimate of marine action in the direction indicated by those who were now advocating the supreme potency of subaerial erosion.

Were we to sum up in a few words the final outcome of the long controversy on the origin of mountains and valleys, we should say that the old view of violent upheavals of the earth's crust has been abandoned. To-day, the prevalent belief is that deformation of the crust has probably as a rule taken place slowly and gradually, and that erosion and denudation have necessarily accompanied the elevation of mountains, so that throughout the whole period of their growth or upheaval they have been subject to continual degradation. However strenuously the sea may have worked upon a gradually subsiding or emerging land, geologists no longer doubt that the modelling of the surface has been effected mainly by the subaerial agents ; it is to these ceaselessly active forces that the shaping-out of mountain and valley is now attributed.

But it is necessary to consider somewhat more closely the geological structure of that great class of original or tectonic mountains of which we have just been speaking. Deformation mountains exhibit three types at least, which may be termed respectively, *folded* mountains, *dislocation* mountains, and *laccolith* mountains. Of these by far the most important are the folded mountains. Nearly all the greater ranges and chains of the globe belong to that group. To such an extent is this the case, that when geologists speak of mountains of upheaval they are usually understood to refer to folded mountains only, the question of their origin having formed the subject of the protracted controversy referred to

above. Dislocation mountains and laccolith mountains are of quite subordinate importance. Indeed it is only within late years that these types have come to be known.

Folded Mountains

As the name implies, these consist mainly of much folded and steeply-inclined rocks. It would be interesting to know whether the crustal deformation, to which they bear witness, was suddenly or slowly effected. It need hardly be said that no one has ever seen a mountain range come into existence, nevertheless geologists are not without evidence in favour of their belief that the process has probably in all cases been more or less protracted. Some ranges owe their origin apparently to one uninterrupted and long-continued lateral thrust. These are the so-called *monogenetic* ranges. Many of the greatest mountain chains, however, as the Himalaya and the Alps, are the result of two or several such movements, separated the one from the other by wide intervals of time. The first appearance of such a *polygenetic* chain would be a series of ranges produced during a single prolonged movement of compression. Next would ensue a pause of longer or shorter duration, followed eventually by renewed lateral thrusting, and the formation of younger folds or ranges flanking the older series; a process which has apparently been repeated many times in the building of some polygenetic chains. It is quite obvious, then, that mountains of this complex character have not been

suddenly evolved. True, the mere fact that upheaval in their case has taken place after successive intervals of repose, does not prove that the crustal movements themselves were not sudden and violent. But if it can be shown that in the case of our youngest mountains the uplifting process has been exceedingly protracted, we shall to some extent be justified in coming to the conclusion that the earlier deformations were probably not more rapidly effected. Now it has been ascertained, as will be indicated more particularly in the sequel, that the rivers flowing from the heart of a great polygenetic chain usually traverse the younger or secondary ranges without having undergone any deflection. It can be proved that these rivers occupy valleys in the central and older parts of the chain which had been excavated long before the younger ranges made their appearance. It is clear, therefore, that if the latter had been suddenly upheaved athwart the old valleys, the rivers must inevitably have been turned to right or left. From the fact that no such divergence or derangement of the drainage has occurred, we can only conclude that the later crustal movement proceeded so very leisurely that the rivers were able to cut their way across the deformations just as rapidly as these developed.

Although all folded chains owe their origin to lateral compression, yet their present aspect—their relief or general configuration—cannot be attributed solely to subterranean action, otherwise it would be in close accord with the geological structure. But this is rarely or never found to be the case. Ex-

ceptionally, it is true, the relief of a chain obviously coincides more or less closely with the disposition of its rocks, long parallel ranges and intervening depressions corresponding to the undulations or foldings of the strata. In such cases the ridges are formed of what are known as *anticlines* or

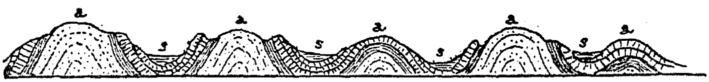


FIG. 18.—Symmetrical Folds of the Western Jura. *a a*, Anticlines; *s s*, Synclines.

saddlebacks, roof-like arrangements of the strata which are inclined in opposite directions from a central axis or axial plane. The intervening longitudinal valleys, on the other hand, occupy *synclines* or troughshaped structures, wherein the strata dip from opposite directions towards a central axis.

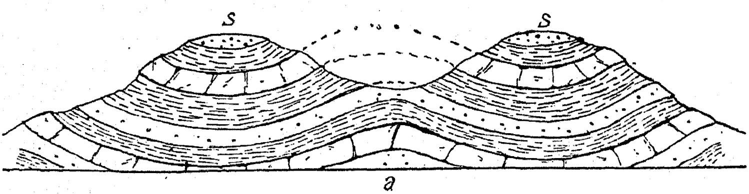


FIG. 19.—Symmetrically Folded Strata. *a*, Anticline; *S S*, Synclines.

A good example is furnished by the ranges of the Western Jura (Fig. 18). But such harmony between surface-form and geological structure seldom obtains; frequently anticlines coincide with valleys and synclines with hills (Fig. 19). Indeed, even in the case of the well-preserved folds of the Jura, much rock has been

removed, especially from the crowns of the anticlinal ranges. The state of preservation of these mountains is indeed exceptional. The adjacent Limestone Alps of north-east Switzerland, belonging to the same period of upheaval as the Jura, exhibit a somewhat similar correspondence between relief and geological structure (Fig. 20). But amongst the mighty mountain masses that rise immediately behind the Limestone Alps we look in vain for the like phenomena. And yet the loftier tracts referred to are geologically only a little older than the Limestone Alps and the Jura, the former belonging to an older, and the latter to a younger stage of the same protracted movement of elevation.

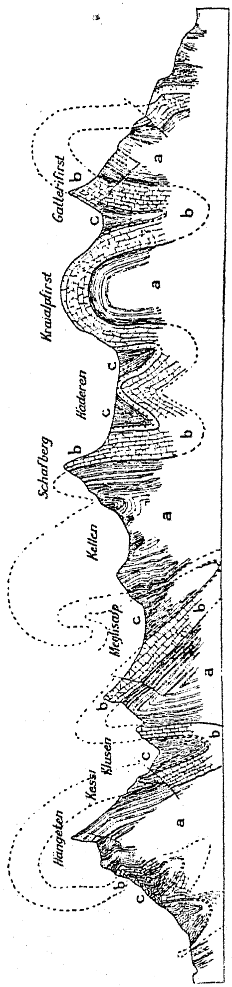


FIG. 20.—Section across the Limestone Alps (Säntis) of north-east Switzerland. (After Prof. Heim.)
a, Marls, shales, breccias, etc. *b*, Chiefly hard limestone. *c*, Impure limestone, shales, etc.

Everywhere, therefore, folded mountains, even the youngest, have been more or less profoundly modified by erosion and denudation. Prodigious masses of rock have been removed, not by the violent action of catastrophic deluges as was formerly supposed, but by the constant and long-continued operation of the same forces

which are still busy sculpturing and reducing heights, and deepening and widening valleys. Partly owing to their greater elevation and more abrupt declivities, the younger uplifts of the globe yield more readily than older mountains to the assaults of the epigene or superficial agents of change. They soar into regions where the subaerial agents act with the greatest vigour, and their steep slopes favour erosion and the rapid removal of detritus from higher to lower levels. Their geological structures, moreover, are frequently weak, and many heights thus fall an easy prey to the elements. Hence in all such regions enormous rock-masses ever and anon collapse, and shoot down from peak and precipice, while landslips on the largest scale are prone to occur. But amongst folded mountains of the greatest age, erosion and denudation, although never ceasing, do not proceed so rapidly. These ancient heights have been much reduced, and have lost the abrupt configuration of their youth. Exposed for untold ages to the attacks of the epigene agents, all their weak rock arrangements have long been demolished, and only the stronger or more resisting ones remain. And thus it is that amongst the oldest folded mountains extensive landslips are of the rarest occurrence. With them external form and internal structure have everywhere ceased to coincide, and relative stability has been attained.

That stability, however, is only relative. The reduction of the older ranges may not be so rapid as that of the more recent elevations, but none the

less it knows no pause. Slowly but surely hills and ridges crumble down, and valleys increase in depth and width. Nothing can arrest the general decay, even the hardest rocks and the most durable structures must eventually succumb. Should the existing sea-level be maintained, a time must arrive when the old mountains shall have finally vanished and given place to low-lying, undulating plains. From the period of youth, as seen in the Jura and the Limestone Alps of Switzerland, down to that of old age, as exhibited in the sorely wasted ranges of such a chain as the Appalachians (Fig. 21),

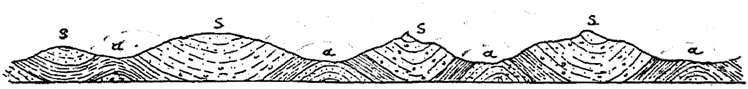


FIG. 21.—Appalachian Ridges of Pennsylvania.

the progress of this gradual dissolution may be followed through all its stages. Nay more, geologists have mapped out the sites of mountains of elevation which had already been levelled to their foundations long before the youngest uplifts of the globe had come into existence. The story of these lost mountains forms one of the most interesting chapters in the stony record, and in the sequel some reference will be made to certain European examples.

Meanwhile let it be remembered that the demolition of a mountain has not often been completed without interruption. Denudation necessarily accompanies the appearance and growth of all mountains, and if upheaval has usually been a protracted process,

then long before a movement of elevation ceased, the configuration of a growing chain must have been more or less profoundly modified. But the tale told by our polygenetic ranges shows us that decay has ever and anon been interrupted by subsidence, the denuded high grounds becoming partially or wholly submerged. New sedimentary deposits thereafter gathered over the drowned land, and often attained a great thickness. Eventually the depressed area began to rise again, and the younger strata which had accumulated on the sea-floor in front of the old denuded ranges were folded and mashed against the latter, while occasionally the older rocks together with the younger overlying accumulations were to some extent interfolded, and even driven forward in successive overlapping sheets of great extent and thickness. In this manner a mountain mass renews its youth and another cycle of erosion commences, to be again interrupted perchance by a period of submergence and accumulation, followed as before by a repetition of upheaval, so complicated is the geological history of many chains and ranges.

Folded mountains usually appear as a series of elongated and more or less parallel ranges, which not infrequently interosculate or merge into one another, the united series extending in approximately straight or gently curved, or, it may be, more strongly arcuate lines, for distances of hundreds or thousands of miles. In all cases the width of the elevated tract is much exceeded by its length. Such a mountain range or chain, after continuing for some distance as one

system, often divides, and the zone of folded rocks is resolved into a series of divergent ranges. Folded mountains may traverse broad, low-lying regions so as to form the backbone of a country; or they may rise along the margins of lofty plateaus. While not a few are far removed from the sea, many fringe the coasts of continents, a position assumed by most of the youngest and loftiest ranges.

The folded structure characteristic of all these mountains varies in complexity. Occasionally, as in the case of the Uinta Mountains, it is of the simplest

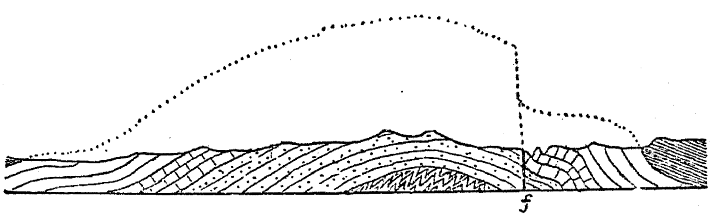


FIG. 22.—Section across the Uinta Mountains—a broad Anticline broken by a dislocation or fault (*f*).

kind, the strata being arched upwards as a single broad saddleback or anticline (Fig. 22). Or the rocks may be arranged in a series of open symmetrical waves or undulations, as in the ranges of the Western Jura (see Fig. 18) and the sandstone mountains of the Carpathians. Usually, however, the structure is infinitely more complex, the strata showing closely compressed unsymmetrical or asymmetrical folds and doublings inclined at all angles, or even overturned and lying on their sides, while ever and anon the structure is still further confused by great fractures and horizontal displacements. No drawing

or even photograph can give an adequate idea of this remarkable architecture. Not only do we see extensive and often highly corrugated duplicatures, some of which may measure many hundreds or even thousands of feet in length, but within each compressed fold we can recognise innumerable subordinate flexures, contortions, and crumplings, varying in importance down to creases and puckers so minute as to be visible only under the microscope (see Plates XIX, XX).

Another phenomenon frequently observed in regions of highly folded rocks is what is known as *slaty*

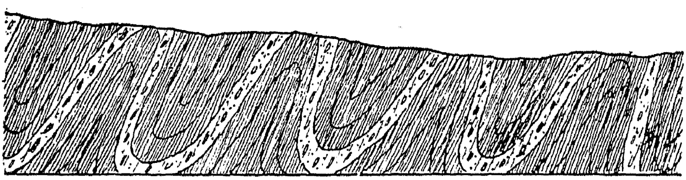


FIG. 23.—Cleavage and Bedding. The undulating lines indicate bedding; the close-set steeply-inclined lines represent cleavage.

cleavage. This structure is usually restricted to those parts of a range where the folds are least complex, consequently it appears most frequently along the marginal zones of disturbance. In the structure referred to the rocks are traversed by close parallel division planes, which coincide in direction with the axes of the folds (Fig. 23 and Plate XXI). When cleavage is well developed the rocks become coarsely or finely fissile, according as they are composed of coarser or finer-grained ingredients. In many cases, moreover, the surfaces of the *cleavage planes* acquire a silvery glaze or lustre, owing to the development of

white mica. As the complexity of the rock architecture increases, however, the cleavage planes begin to disappear, and are by and by replaced by the structure known as *schistosity*. Schistose rocks are more or less distinctly crystalline in texture, the component minerals being arranged in rudely alternate lenticular layers or laminæ, as in those well-known rocks, mica-schist and gneiss. Now it is specially worthy of note that rocks of this type predominate in those parts of a mountain chain where folding and contortion are most conspicuous.

The facts thus briefly indicated have convinced observers that folded mountains owe their origin to powerful lateral compression. The folds themselves are evidence sufficient in itself to prove the case, but the several additional structures referred to make assurance doubly sure. Examined under a microscope the constituents of a fine-grained well-cleaved rock, like common roofing-slate, are seen to be flattened out and extended in the direction of the cleavage planes, and these planes, it will be remembered, have the same trend as the axes or axial planes of the large rock-folds. Obviously the folds have been strongly compressed, and the slaty structure has been superinduced by this squeezing process. Even the unaided eye may often detect conspicuous evidence of crushing and squeezing. The stones in a conglomerate, for example, may be flattened into lenticular forms (Plate XXII, 1), and drawn out as if by compression acting in a direction at right angles to the trend of the large anticlines

and synclines; and the same is the case with fossils, which in highly folded strata are frequently so distorted that their species can with difficulty be determined. Both stones and fossils, it may be added, have often been deformed in this remarkable manner without breaking.

Further, careful examination of the crystalline rocks, which so often enter into the formation of a complex mountain region, shows that these have sometimes been subjected to such intense pressure, that their constituent minerals have been crushed and shearing has ensued, the elongation, as in slaty cleavage, taking place at right angles to the pressure. Whole rock-masses, in short, have been compelled to flow as if they were plastic bodies. So great has been the force applied and the heat developed that complex chemical and mineralogical changes have been induced, even fragmental rocks of aqueous origin having become crystalline and schistose (Plate XXII, 2). In a word, *metamorphism*, more or less pronounced, is a frequent concomitant of rock-folding on the large scale, and especially affects those rock-masses which have been most severely pressed and mashed together in a mountain chain.

To sum up: we note that in the less closely folded and corrugated rocks of a mountain range the character they possessed before deformation took place may still be recognised; they may be cleaved and rendered in this way more fissile, but these changes are not so considerable as to prevent us perceiving what the rocks originally were. As we approach

PLATE XIX.

1. CONTORTED ALPINE LIMESTONE (BANDED).
Nearly natural size.

2. CONTORTED LIMESTONE (BANDED), GLEN MOHR, GLEN TILT.
Photo, Dr Flett.

PLATE XX.

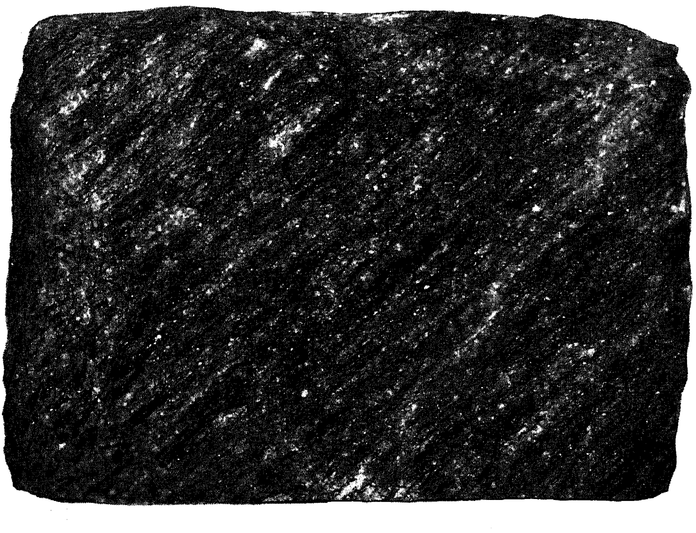
CONTORTED SCHISTS, ETC., BEN VRACKIE.
Photo, H.M. Geological Survey.

CLEAVAGE IN STEEPLY-FOLDED SLATES AND PHYLLITES, NEAR CARRIG NAM FEAR, ISLAY.

Photo, H.M. Geological Survey.

[*Between pages* 80 *and* 81.

1. SCHISTOSE CONGLOMERATE. Nearly natural size.
(From Lehmann's *Entstehung der altkrystallinischen Schiefergesteine.*)



2. GNEISS. About two-thirds natural size.

[*Between pages* 80 *and* 81.

the region of highly complicated structures, however, rock changes become more and more marked, until frequently crystallisation and foliation combine to destroy all original characters. Sedimentary rocks of various kinds are metamorphosed into schists, often crumpled and gnarled, limestones are converted into marble, while massive igneous rocks, such as granite, have likewise been crushed and foliated; nay, even ancient crystalline schistose formations have been reconstituted, new planes of foliation obscuring and frequently obliterating older structures of the same kind.

Having now outlined the evidence which leads to the belief that the peculiar architecture of folded mountains is the result of lateral compression, we may next consider certain general structural features of a typical mountain range. It is obvious that particular investigation of the folds ought to throw some light on their origin; we should be able by careful examination to ascertain the direction from which came the lateral thrust that produced them. If the crests of most of the anticlines (especially of those that approach a recumbent attitude) look towards the north, for example, then the movement must have been northerly. Such an inference is strongly supported by the fact that the extensive horizontal or approximately horizontal displacements in a mountain range have the same trend as the great majority of the folds. If the latter lean over to the north, the displaced rock-masses are found to have moved towards the same point. Horizontal displacements of the

kind referred to have usually played a conspicuous rôle in the process of mountain-making. The rocks have yielded to thrust not only by folding, but by rupturing. In the case of recumbent folds, the closely compressed anticlines have often given way, and one limb of a fold has been thrust forward over and beyond the other (see Fig. 30, p. 94). In other places the strata would seem to have yielded without preliminary folding. Vast slices or sheets of rock, hundreds or even thousands of feet thick, have been forced successively one over another, travelling it may be for many miles up gentle inclines or along approximately horizontal planes. Thus, partly by folding and partly by rupture and displacement, the constituent strata of mountain uplifts have often been turned upside down, and the oldest rocks thrust forward over the youngest.

All these and other phenomena resulting from compression are nowhere better exhibited than in the Alps, the leading features of whose architecture will be sketched in the following chapters.

CHAPTER V

ORIGINAL OR TECTONIC MOUNTAINS—*continued*

The Architecture and Origin of the Alps. Geological History of the Mountains. Types of Rock-structures ; Symmetrical, Asymmetrical, and Contorted Folds ; Reversed or Overthrust Faults ; Recumbent Folds and Thrust Planes ; Translated Rock-Sheets. Helvetian, Lepontine, East Alpine, and South Alpine Sheets. Nagelfluh Conglomerates. Folding of the Säntis and the Jura Mountains. Prof. Steinmann's Views of Alpine Structure. Blätter or Transcurrent Faults.

No system of mountains has been so long and so laboriously studied by geologists as the great chain of the Alps. Every decade since the days of De Saussure has added to our knowledge of its structure and history, but until quite recently much still remained obscure and apparently inexplicable. Although it cannot be asserted that all the secrets of the Alps have now been unveiled, there can be little doubt that some of the most important problems suggested by the complicated and puzzling phenomena have at last been solved. The tale revealed by the rocks is a very remarkable one, and often, it may be added, hard to follow. If attention be fixed, however, on the chief points—on the salient features of the evidence—it is possible to obtain a not inadequate

conception of the leading ideas held by Swiss geologists as to the architecture and origin of the chain.

In the following brief account of the rocks and rock-structures of the Alps, only meagre reference can be made to the geological history of the region. The long and involved story which the rocks have to tell of successive geographical and climatic changes cannot be discussed in these pages. Our present aim is merely to acquire as clear an idea as we can of the remarkable crustal movements that resulted in the formation of the chain, and to note the part played by denudation in the evolution of the mountains. It may be well, however, before proceeding further, to consider in a very general way how the stones used in the building of the Alps were brought together.

From a geological map of the area we learn that the constituent rock-masses belong to two great series : a lower or basement set, consisting chiefly of gneisses, schists, granites, etc., and an upper or overlying division of aqueous strata, such as limestones, shales, sandstones, etc. These latter formations rest upon the highly worn or much denuded surface of the basement crystalline rocks, and the latter are therefore, throughout extensive tracts, entirely covered and concealed. In many other places, however, the younger series is absent, and the old crystalline rocks are thus exposed over certain broad areas. They form, for example, the lofty massifs of Mont Blanc and the Aiguilles Rouges, the Bernese and Gotthard

Alps, etc., and may be said, in a word, to constitute the backbone of the Swiss Alps.

With the particular history of the basement rocks we are not concerned. All that need be noted is the simple fact that they represent the southern maritime tract of an ancient land which had come into existence during the closing stages of the Palæozoic era. That land was throughout more or less mountainous in character and extended far north into what is now middle Europe. It was bounded on the south by a much more extensive Mediterranean than that of our day. Coming into existence in post-Carboniferous times, it persisted as a continental area for a very prolonged period, during which it suffered excessive denudation. Its chains and ranges were thus gradually reduced and degraded, and over wide tracts became replaced by undulating low grounds. Here and there, however, more or less prominent heights survived—the stumps and torsos, as it were, of the old mountains. Before the complete reduction of the land could be accomplished a movement of subsidence ensued. This depression affected the Alpine region especially, but was likewise experienced throughout extensive areas of middle Europe. Slowly the reduced Alpine land sank; its more prominent heights enduring for a long time as gradually diminishing islands. The sinking movement, although now and again interrupted, may be said to have prevailed throughout the whole course of the protracted Mesozoic era. Immense deposits of sediment had thus ample time to accumulate over the slowly-subsiding

sea-floor. When the dawn of the Cainozoic or Tertiary era approached, the ancient Palæozoic Alpine land had all but vanished, only a few small islands remaining, and by and by these too sank in the broadening Mediterranean.

In this way the drowned Palæozoic country was at last completely buried under a varying thickness of sediments — mostly marine. The submergence appears to have been greatest in the south and least in the north, but what are now the central parts of the Swiss Alps would seem to have been as deeply depressed as any. Owing to the irregular depths of the Mesozoic and Cainozoic seas, the sediments naturally attained their greatest thickness over what had been the low-lying tracts of the drowned land, and thinned away across the heights which had for so long a period survived as islands.

Thus the conditions that obtained over the Alpine area just before the great crustal movements of the Cainozoic era began were simply these:—an ancient much reduced mountain-land submerged and covered throughout by a vast succession of horizontal strata, reaching in some places a thickness of 10,000 or 15,000 feet. The buried land is built up chiefly of crystalline masses and some Carboniferous strata, while the overlying bedded series range in age from Permian and Triassic down to early Cainozoic. Geologists have no means of computing the time required for the accumulation of that most impressive succession of formations. But when we think of the many geographical and climatic changes—of the

extensive evolutions of life-forms — the successive appearance and disappearance of floras and faunas—that took place between the close of the Palæozoic and the dawn of the Cainozoic era, we are forced to admit that many millions of years must have been consumed in merely bringing together the materials for the construction of the present Alps upon the site of the old Palæozoic land.

The accompanying diagram (Fig. 24, p. 88), after Professor Schmidt, is a schematic section across the Swiss Alpine area, designed to show the general disposition of the older (A) and younger (B) series of rocks, before the crustal folding of Cainozoic times had supervened. The older rocks, it will be observed, occupy more or less highly inclined positions, and are abruptly separated from the overlying younger strata which are horizontal, and vary in thickness owing to the inequalities of the sea-floor over which they accumulated. Attention may also be called to the occasional abundant presence of rolled or water-worn stones in the basement-beds of the (B) series, and especially to the "breccias" which are so well developed in the several systems (Triassic, Jurassic, Cretaceous, and Eocene) in the central part of the area. These breccias are masses of angular fragments, derived chiefly from the breaking up of the underlying old crystalline rocks, and are most plentiful, therefore, in the deposits that accumulated round the coasts of the islands which were the last parts of the Palæozoic land to disappear.

The Alps may well be taken as a characteristic

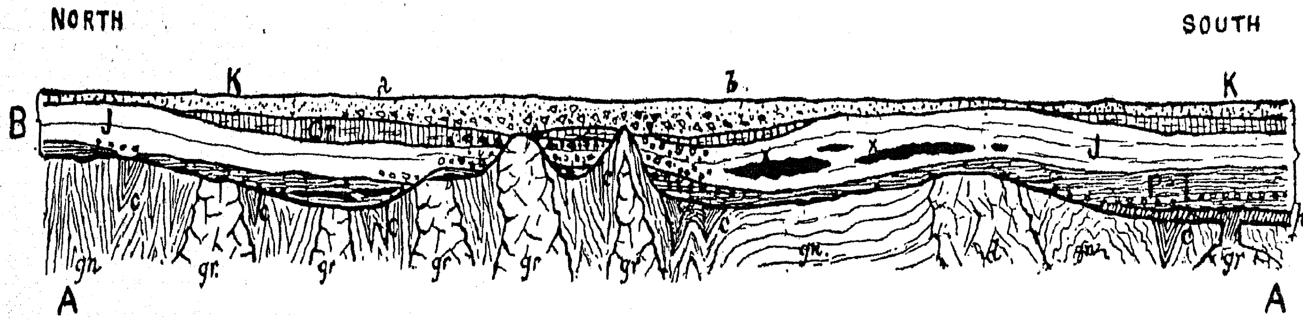


FIG. 24.—Schematic Section across the Swiss Alpine area, showing the general disposition of the older (A) and younger (B) series of rocks before the crustal folding of early Cainozoic times. (After Professor Schmidt.)

A, Highly denuded Palæozoic (post-Carboniferous) land; *gn*, gneiss, etc.; *c*, interfolded Carboniferous strata; *gr*, granite, etc.; *d*, diorite; *p*, quartz-porphyry.

B, Strata accumulated over A during period of prolonged submergence; P-T, Permian and Triassic; J, Jurassic; Cr, Cretaceous; K, Eocene; XX, Igneous rocks. Breccias and conglomerates developed chiefly in central tract between *a* and *b*.

[The breadth from north to south of this area, before folding took place, was apparently not less than 370 miles; after folding it was reduced to about 100 miles.]

example of folded mountains—a class which, as already indicated, includes all the greatest chains and ranges of the globe—the Himalayas, the Rockies, the Andes, and many less conspicuous heights. All these, as we have seen, owe their origin to movements of compression, whereby the constituent rock-masses have been buckled up, dislocated, and displaced. The movements referred to are doubtless due to the wrinkling of the earth's crust over the slowly cooling and contracting interior. The crust having already cooled cannot contract to the same extent, and therefore as it subsides it is compelled to accommodate itself to the shrinking nucleus by folding and fracturing. The relief from compression may be manifested by wide regional deformation of the crust—that is, by the bulging upward of extensive areas, accompanied not infrequently by much subordinate warping, flexing, and folding of a more or less gentle or moderate character. Cases of this kind are termed "regional uplifts." In other cases, however, the crust yields along some determinate zone of great length, it may be, but of relatively narrow width. Under such conditions compression usually results in the formation of more or less numerous steeply-inclined folds, and in the horizontal displacement of great rock-sheets. The general character of the rock-folds and displacements in these "axial uplifts" naturally varies according to the degree of crustal compression. When the lateral pressure has not been excessive, the folds may be more or less symmetrical in form, and relatively inconsiderable

horizontal displacements may occur. But when crustal compression has been most vigorous, the resulting flexures, folds, and rock-displacements are correspondingly pronounced and often astonishingly complicated.

In the preceding chapter some reference was made to the characteristic structures met with in folded mountains, and it was pointed out that these structures varied much in complexity. Where the degree of crustal compression has not been excessive,

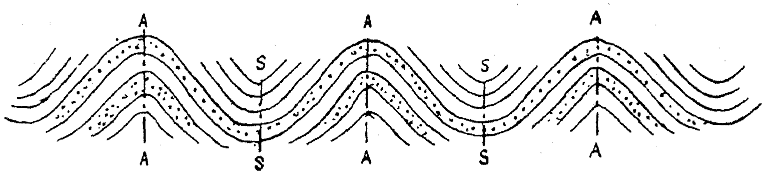


FIG. 25.—Symmetrical Folds. AA, Anticlines; SS, Synclines. The upright dotted lines indicate the vertical axial planes.

the flexures and folds may be approximately symmetrical, as seen in the accompanying diagram (Fig. 25; see also Fig. 18, p. 72). In symmetrical folds the axes or axial planes are vertical, and the folds frequently tend to be more or less "open"; or in other words, the limbs of the several folds are not closely compressed. The dip or inclination of the strata, therefore, is not usually at a high angle—is often much less, indeed, than that shown in the diagram.

In asymmetrical folds (Figs. 26 and 27), on the other hand, the axial planes are not vertical but inclined, while the dip of the strata tends to be steep—

and steeper on one side than the other—and the folds, therefore, are no longer "open" but "close." Not infrequently, however, asymmetrical folds may be more or less "open," especially when their axial

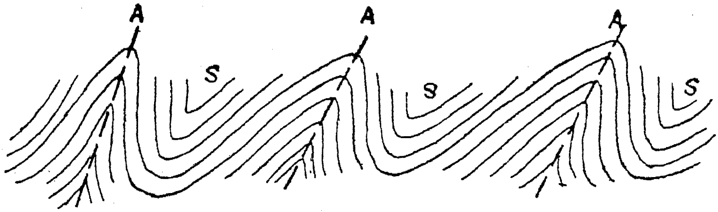


FIG. 26.—Asymmetrical Folds with Inclined Axial Planes.

planes approach verticality (see Fig. 26). When their axial planes are less highly inclined, asymmetrical folds often afford strong evidence of having experienced much compression. Not only are the

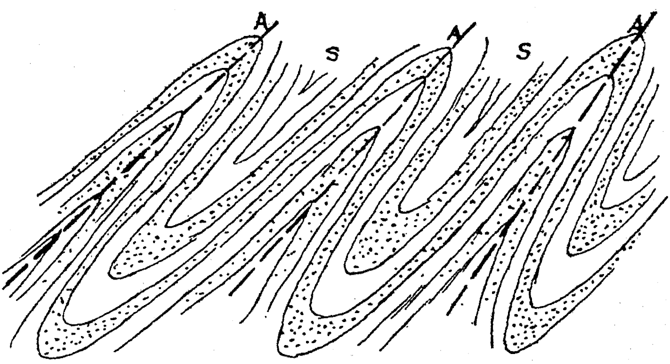


FIG. 27.—Much Compressed Asymmetrical Folds; beds becoming thin in the limbs and thickening in the bends or cores.

strata steeply inclined, but they show more or less pronounced "inversion"—that is to say, the beds are overturned to such an extent that a vertical shaft sunk through one of the anticlines would encounter the same bed twice. Fig. 27 represents a series of

such highly-compressed folds. The beds in the cores of the anticlinal and synclinal folds appear to have been thickened, while the same beds in the limbs have become attenuated. The strata, in short, have obviously been rendered plastic, the materials subject to extreme pressure having flowed away to accumulate in the bends where compression was less severe.

Rock-folds, however, are often much more highly confused and complicated. Not only are the strata flexed and doubled up in great anticlines and

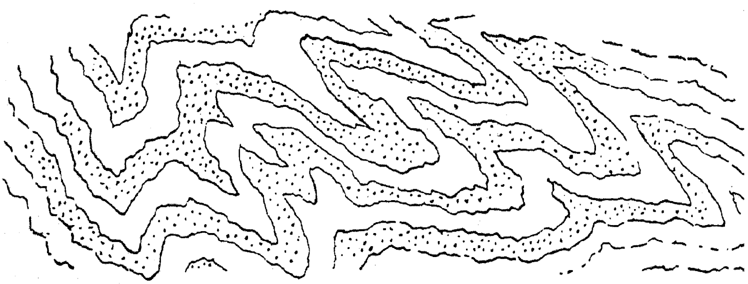


FIG. 28.—Contorted Folds.

synclines, with axes lying at all angles, but the individual beds constituting the folds may be exceedingly crumpled, puckered, and contorted, as shown in Fig. 28 (see also Plates XIX, XX).

Reference has been made to the attenuation so frequently seen in the limbs of highly compressed folds. The process of compression has often proceeded so far as to result in the squeezing out of a limb altogether. Fig. 29, p. 93, illustrates how the limb of a fold (A) under compression gradually becomes more and more attenuated (B), until eventually it is

replaced by what is known as an "overthrust fault"—the fold, in fact, has obviously given way, and the overlying portion has travelled upward along a plane

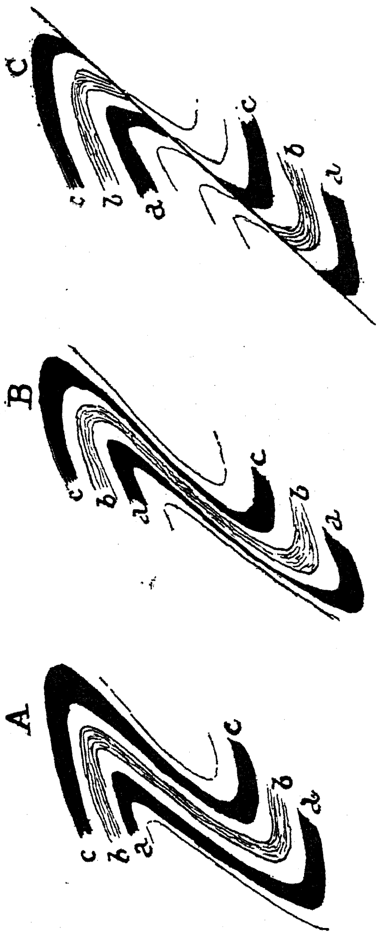


FIG. 29.—Stages in the Passage of a Highly-inclined Fold into a Reversed or Overthrust Fault.

of displacement (c). Faults of this steeply-inclined character are of common occurrence in all mountains of uplift, but the degree of displacement is seldom

considerable. In short, they are usually only of local and subordinate importance.

But when the axial plane of a great asymmetrical fold approaches horizontality and becomes replaced by an overthrust fault, the upper limb of such a *recumbent* fold (as it is called) may be shifted for a distance of many miles. The accompanying illustration (Fig. 30) represents a fold of the kind which has yielded to tangential pressure, the upper limb having travelled from left to right along the "thrust-plane"

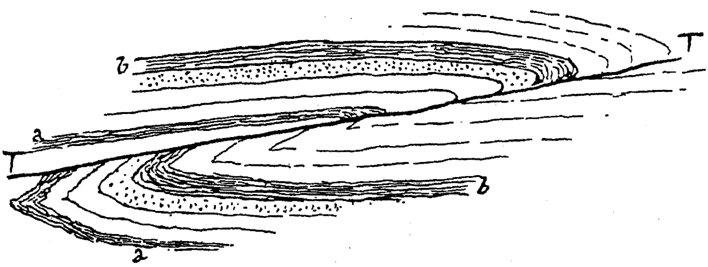


FIG. 30.—Faulted Recumbent Fold. TT, Thrust-plane.

TT. In great mountain uplifts, such as the Alps, ruptured recumbent folds occur on a gigantic scale, the rocks constituting the translated upper limb of a faulted fold often occupying an area many square miles in extent, and attaining a thickness of several thousand feet.

But displacements on this grand scale are not necessarily always preceded by folding. Frequently the rocks subjected to compression have yielded without any preliminary doubling or buckling up, and enormous slices or sheets have been driven successively for miles one over another. A great translated

rock-sheet, resting upon a well-marked thrust-plane, is often accompanied by more or less numerous minor reversed faults or thrusts, disposed at an oblique angle

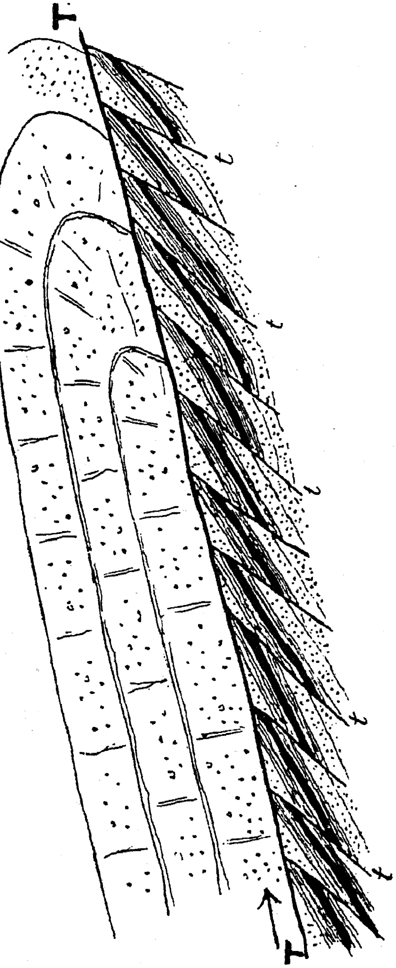


FIG. 31.—Translated Rock-sheets. *tt*, Minor thrust-planes or reversed faults due to tangential pressure, causing frequent repetition of strata = *imbricate structure.* TT, Major thrust-plane along which the higher-lying rock-sheet has been driven in the direction indicated by the arrow. The appearance of folding is probably the result of friction along the thrust-plane, causing the brow of the rock-sheet to curve over and become inverted.

to the major "thrust-" or "sole-plane." These smaller faults often cause frequent repetition of the strata, forming what is known as "imbricate structure" (see

Fig. 31, p. 95). The major thrust-planes are usually more or less gently inclined, while the minor faults are generally steep. It may be noted further that a translated rock-sheet, as its terminal front is approached, may show a certain degree of overfolding, and thus simulate the appearance presented by the upper limb of a ruptured recumbent fold. But the overfolding in question would seem to be the result of friction along the thrust-plane, causing the brow of the sheet to curve over and become inverted.

Such are some of the more notable structures met with in folded mountains, the most conspicuous feature being inversion of one kind or another. So that partly by asymmetrical folding, partly by the rupturing of vast recumbent folds, or by direct displacement of great rock-sheets along horizontal or inclined planes, the oldest rocks in a mountain of uplift frequently overlie the youngest, each kind of crustal deformation having resulted from an irresistible thrust in some particular direction.

The great crustal movement to which the present Alps owe their origin followed a general northerly direction. It is, of course, hard to say to what extent the area undergoing compression was affected during the earlier stages of the movement. The probabilities are, however, that the first notable result of pressure would be the elevation of the sea-floor, and the appearance of a broad flat land extending over what is now the Alpine area. Even at that early stage a certain amount of warping of the new land surface may have taken place, the ground possibly rising and falling in

long gentle undulations. At considerable depths from the surface, however, crustal deformation would be more pronounced. The folds, at first symmetrical, would become gradually deformed and distorted or asymmetrical, the crowns of the anticlines leaning over more and more in the direction of movement, until they assumed a recumbent position and finally yielded to tangential pressure. Great rock-sheets of various thickness and extent would then begin to move up gentle inclines or to creep along approximately horizontal thrust-planes. Meanwhile, the deeper parts of the folds, the synclines or so-called "roots," tarrying behind, would tend under continued pressure to assume steep and vertical positions.

According to Swiss geologists the earliest "Decken" or rock-sheets to invade the northern zone of the Alpine area originated in a series of folds that were developed along the southern borders of what is now the lofty Aar massif, which as yet had not been elevated. The "roots" of the folds in question can be followed, it is believed, in a north-east and south-west direction from Chur to beyond Martigny. These earliest translated masses are known collectively as the "Helvetian sheets." They consist chiefly of Triassic, Jurassic, Cretaceous, and Eocene strata, which have been driven bodily forward in North Switzerland over strata belonging to the same geological systems. Thus it happens that north of the Aar massif the same formations occur in duplicate, the exotic rock-sheets resting upon Mesozoic and Cainozoic strata which are autochthonous or native

to the region; in a word, the latter occur *in situ*, they have not been moved from the place where they were originally deposited as sediments. A well-marked zone of these autochthonous strata extends at a high level along the north front of the Aar massif, from the Tödi (Plate XXXVI) in the north to the Balmhorn in the south (Plate XXXVIII). It is worthy of note that both the exotic and the autochthonous Mesozoic strata have an essentially central European facies—that is to say, the rocks themselves and their fossil organic remains are more nearly related to those of central Europe than to the corresponding fossiliferous strata of the southern Alpine area, the facies of which is Mediterranean.

A second series of folds, developing into horizontal or inclined thrust-planes, appeared further south, chiefly south of the Gotthard massif, which, like the Aar massif, had not as yet been elevated. This complex of imbricated and overlapping "Lepontine sheets," as they are called, moving gradually northward, eventually overspread and largely concealed the Helvetian sheets. The Lepontine rock-sheets, like their predecessors, consist mainly of Mesozoic and Cainozoic strata; but they are distinguished from the latter in several respects, more especially by their Mediterranean facies, and by the presence of many breccias and certain igneous and other kinds of rock which are quite foreign to the Helvetian sheets. These and other phenomena characteristic of the Lepontine sheets show that this second complex of translated rock-sheets has

travelled northwards from the central and southern Alpine area.

A third complex, known as the "East Alpine" sheets, originated further south still, and advanced over the Lepontine sheets; while yet a fourth series, the "South Alpine," was driven forward from the very borders of the Alpine area in north Italy, so as to overlie the preceding East Alpine sheets (see Map, Fig. 32, p. 100).

Thus, several series of complex folds and overthrust rock-sheets were developed successively in the northern, in the central, and finally, in the southern zones of the Alpine area, each complex following, and eventually overtaking, and to some extent overlapping its predecessor. While the translation of these several sheets was in progress, the downward bends of the original folds, the deep-seated "roots," although relatively stationary, were becoming ever more compressed and steeper, so as to occupy less space, and the interval separating one sheaf of "roots" from another necessarily diminished in proportion.

The roots of the latest or uppermost rock-sheets ("South Alpine," or "Crystalline" as they are sometimes termed) are succeeded southwards by strata which have not been pushed out of place; they are aboriginal or autochthonous, and range in age from early Mesozoic down to late Cainozoic. They are inclined towards the south at a somewhat high angle, but as the plains of the Po are approached, the angle of dip rapidly decreases. Nowhere do they show

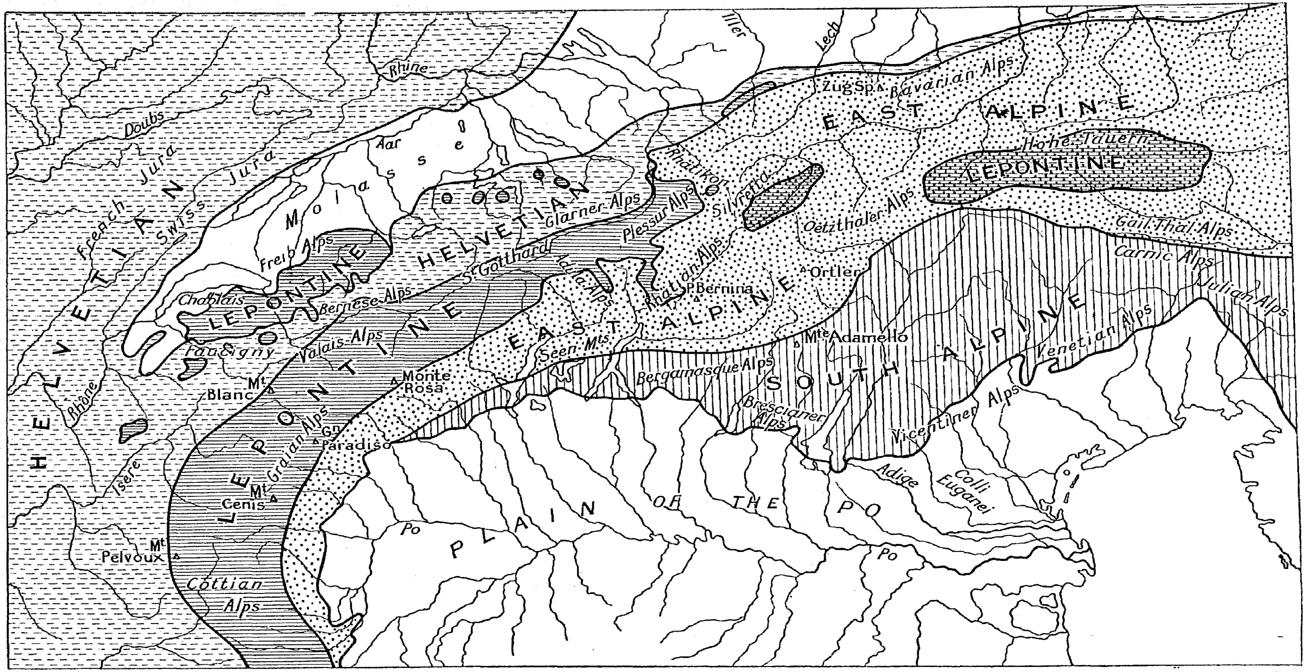


FIG. 32.—Sketch-map of the Four Great "Rock-groups" of the Alps. (After Professor Steinmann.) *Bartholomew, Edin.*

These groups are termed respectively the Helvetian, the Lepontine, the East Alpine, and the South Alpine, each group having its own characteristic facies. The Helvetian is indicated by interrupted horizontal lines; the Lepontine by continuous horizontal lines, the inliers of the same sheet which look through the "windows" in the overlying East Alpine sheet, being shown by dots as well as lines; the East Alpine is indicated by dots; and the South Alpine by vertical lines.

over-folding or horizontal displacements. In these respects, therefore, the autochthonous strata occurring along the southern borders of the disturbed area differ from the autochthonous strata occupying the corresponding position on the north side of the mountains, as will subsequently be pointed out more particularly.

While trying to picture to ourselves the conditions that obtained when rock-sheet after rock-sheet was being driven forward, we must bear in mind that the existing lofty mountain ranges had not as yet made their appearance. There may well have been a general bulging upwards of the whole compressed area, but the dominating massifs of our day, Mont Blanc, the Aiguilles Rouges, the Gotthard and Aar massifs, had not as yet shown themselves; their elevation belongs to a later phase of the great crustal movement. The invasion of the northern zone by exotic rock-sheets, therefore, was not opposed by any insuperable mountain barrier. When the translation of successive rock-sheets had been completed, the ancient Palæozoic land lay deeply buried in Switzerland, the earliest travelled rock-sheets being covered and concealed by their successors. If it took millions of years to bring together materials for the construction of the Alps, long æons were required for the process of building, for piling up rock-sheet upon rock-sheet. Crustal movement had begun before the close of Eocene times, was continued throughout the subsequent Oligocene and Miocene periods, and had apparently not quite ceased

before the advent of prehistoric man, if indeed it has even now completely died away. In a word, the movement of compression must have extended over several millions of years.

We come now to a very interesting episode in the history of the Alps. When the last of the exotic rock-sheets had ceased to move, north Switzerland appears to have been represented by an elevated tract extending in a north-east and south-west direction. In Miocene times an inland sea covered the site of the present Jura Mountains, and laved the north front of the Alpine area, where it maintained its position for a prolonged period. This is proved by the simple fact that thick masses of sediment had time to gather over the floor of the Miocene sea, all of them derived from the denudation of the Alpine area. Torrential streams and rivers swept down to the sea vast quantities of shingle and gravel, and doubtless waves ate their way into the land, and thus played a part in the work of degradation and accumulation. The shore-deposits of that ancient sea can still be followed all along the north front of the Alps, where they form a conspicuous range of subalpine hills and mountains that vary in height from about 4000 feet to upwards of 6000 feet. They extend almost continuously from Lake Constance to Lake Thun. Further west and south-west they fringe the Freiburg Alps, but in this region they are less conspicuous. The shore-deposits in question consist largely of massive conglomerates

and pebbly sandstones, etc., known as "Nagelfluh" (Molasse).

The relation of the Nagelfluh to the exotic rock-sheets of Switzerland is of absorbing interest to the geologist. It would appear that when the Miocene shore-deposits began to accumulate, the great rock-sheets derived from the south had become passive. So far as we know, indeed, there may have been at that time a more or less prolonged cessation of all crustal movement. On the other hand, it is quite possible that crustal creep may never have been quite interrupted. Earth-movements of the kind, so far as we have evidence to show, are usually protracted, and do not interfere with the processes of denudation and deposition. But whether or not all crustal deformation had temporarily ceased during the heaping of the Miocene beach-gravels, it is certain that the formation of the latter marks the close of the first phase of the great crustal movement.

That phase was characterised above all by the translation from south to north of massive sheets of rock, but no such remarkable displacements would appear to have taken place during the second and final phase of disturbance. Further, it may be noted that during the first phase the fundamental crystalline rocks of the central and northern zones of the compressed area were left comparatively undisturbed. They had been to some extent, it is true, sharply folded along with the younger overlying strata, but none of these folds had developed into extensive displacements—the masses of ancient crystalline rocks

had retained their position, while being traversed by rock-sheet after rock-sheet. During the second phase of deformation, however—that, namely, which supervened after the heaping together of the Miocene beach-gravels — the fundamental crystalline rocks found relief from renewed compression partly by folding but chiefly by rising vertically. In a word, the grand massifs of Aar-Gotthard, of the Aiguilles Rouges, and Mont Blanc slowly bulged upwards. At the same time the irresistible thrust that caused these upheavals affected all the regions lying to the north and north-west. The autochthonous or native strata of Switzerland, and the overlying exotic rock-sheets, which had already been much reduced by denudation, were now compressed into a succession of great asymmetrical folds, the crowns of which as usual leaned forward in the direction of movement. At the same time the subalpine tracts and the immediate forelands of the Alps became relatively depressed.

Long before this stage, however, the upper rock-sheets in north-east Switzerland had been largely denuded away, leaving the underlying Helvetian sheets exposed over an extensive area. Now strongly compressed, these sheets rose in a series of gigantic folds, and were thrust with such persistence against the massive Miocene conglomerates that the latter were doubled back upon themselves and overridden. Nor was the disturbance confined to this border region; it affected the entire Alpine area, all the contiguous low-lying Molasse land, and the region of the Jura beyond. It was at this particular stage,

in fact, that the folded ranges of the Jura came into existence. The upheaval of these mountains, in a word, was coeval with that of the lofty limestone ranges of the Säntis (see Fig. 20, p. 73, and Plates XL, XLI).

It is not easy to realise the changes that took place during the first and second phases of the mountain-making process within the Alpine area, but the accompanying diagrams (Figs. 33 and 33*a*, pp. 106 and 107) by Professor Steinmann may serve to illustrate the theoretical conception of the several rock-sheets as much flattened and greatly extended recumbent folds. In A we see the original position of the several rock-masses before crustal movement commenced. The Mesozoic rocks of the northern zone are indicated by 1, while 2 and 3 represent those of the central and southern zones respectively, the old crystalline rocks (black) underlying all. B shows the formation of the recumbent folds, which appear as rock-sheets. In C these rock-sheets are represented as having undergone great denudation, and the Miocene beach-deposits, etc. (Molasse), are seen resting upon the eroded surface of the sheets. D shows the results of the second phase of crustal movement. The fundamental crystalline rocks have now been relatively elevated, as in the Finsteraarhorn massif, while the area to the north has been relatively depressed, the Molasse being buckled up and overlaid by the folded rock-sheets. In these sections Professor Steinmann has necessarily ignored subordinate details, and suggests only the dominating features of

the geological structure as conceived by Swiss geologists. The lines continued above the surface

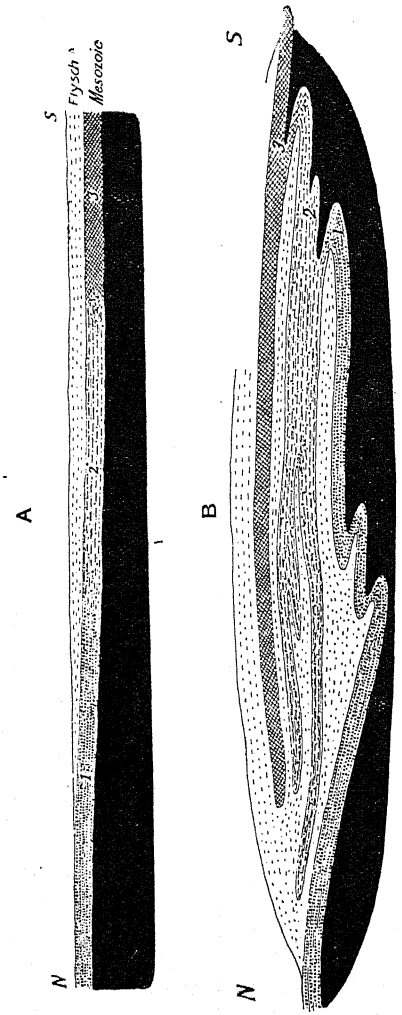


FIG. 33.—Schematic Representation of the Evolution of Mountain-structure in the Alps of North Switzerland. (After Professor Steinmann.)

A shows the stratified rocks (Mesozoic and Flysch) resting in undisturbed position upon the old crystalline rocks (black), the crustal movements not having commenced. The figures 1, 2, 3, indicate the three distinctive "facies" of the Mesozoic systems that succeed each other, from north to south. (This diagram must be supposed to be double the size of either B, C, or D, for it represents the region before compression had taken place.)

B represents the formation of successive rock-sheets, one having moved over another. The uppermost rock-sheet has its "roots" furthest south.

of the ground (D) indicate the rock-masses removed by denudation.

There is one characteristic of the Helvetian folds of the Säntis to which brief reference may be made.

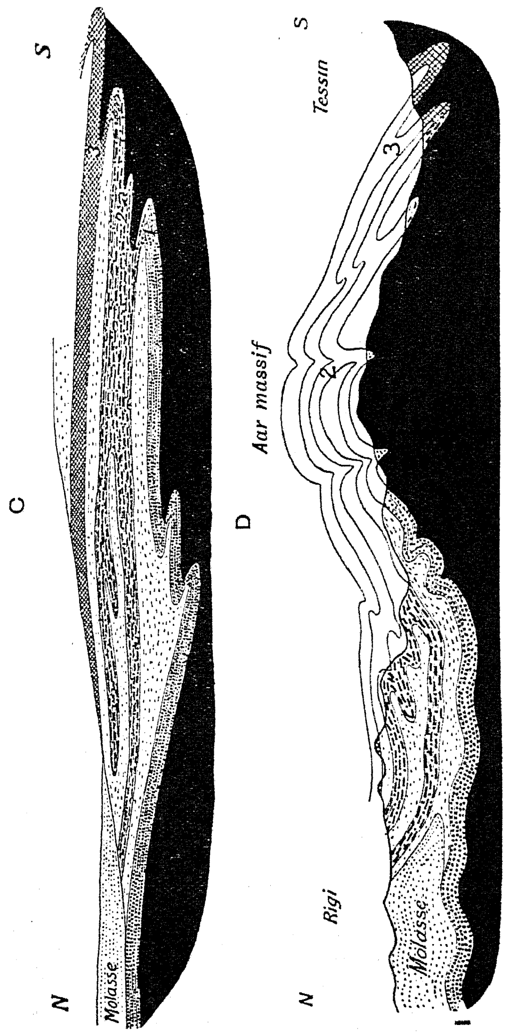


FIG. 33*a*.—Schematic Representation of the Evolution of Mountain-structure in the Alps of North Switzerland. (After Professor Steinmann.)

C shows the region after the rock-sheets had suffered much erosion. The Miocene Molasse is seen resting upon a denuded surface.

D displays the general aspect of the region after the second phase of crustal movement. The Aar massif has become relatively elevated, and the foreground on the north has been relatively depressed. The rock-sheets have been buckled up and overthrust upon the Molasse. The lines continued above the surface of the ground indicate the amount of rock removed by denudation.

They present certain features which distinguish them from the great recumbent folds occurring well within

the Alpine area. The latter originated at considerable depths, and were subject, therefore, to the weight of enormous rock-masses, so that when lateral compression ensued they behaved like plastic bodies, and were flexed, sharply-folded, puckered, and crumpled without breaking. Along the north front of the Alps, however, the strata that were thrust against the Nagelfluh, not being loaded down to nearly the same extent, did not become plastic under the folding process, and consequently were cracked, fissured, fractured, and shattered.

It is further worthy of note that during the latest phase of crustal deformation, to which the folds of the Säntis and the Jura bear witness, no great vertical displacements or "normal faults," as they are called, affected those regions. All the movements were horizontal. Besides the thrust-planes so often referred to, the only "faults" observed in the Limestone Alps are those shallow dislocations called *Blätter* by Swiss geologists. These are indeed vertical, and traverse the folds of the Säntis at approximately right angles, but their horizontally grooved and striated faces demonstrate that the rock-movement was lateral and not vertical: they are, in short, what we should call "transcurrent faults" or "transverse thrusts." We can hardly doubt that they were caused by the same thrust as that which compressed the strata into folds, for they all die out downwards, and are in fact confined to these folds. Possibly they owe their origin to the unequal resistance offered by the great masses

of the Miocene molasse to the advance of the Helvetian folds, which may have induced strains and stresses in the latter to which they yielded by snapping across, so as to allow one sundered segment to move forward in advance of another.

CHAPTER VI

ORIGINAL OR TECTONIC MOUNTAINS—*continued*

Exotic Rock-sheets almost completely removed from Central Massifs, but still well represented in North Switzerland. Exotic Rocks in Miocene Conglomerates. "Erratics" in Flysch. "Klippen" or Drongs. Speculations as to Genesis and Movement of the Rock-sheets. Highly denuded Aspect of the Several Sheets. "Double Folds" and "Mushroom Folds." Inversion the Outstanding Feature in Structure of Alps. Mr Bailey Willis on Alpine Structure. Width of Alpine Area before Compression.

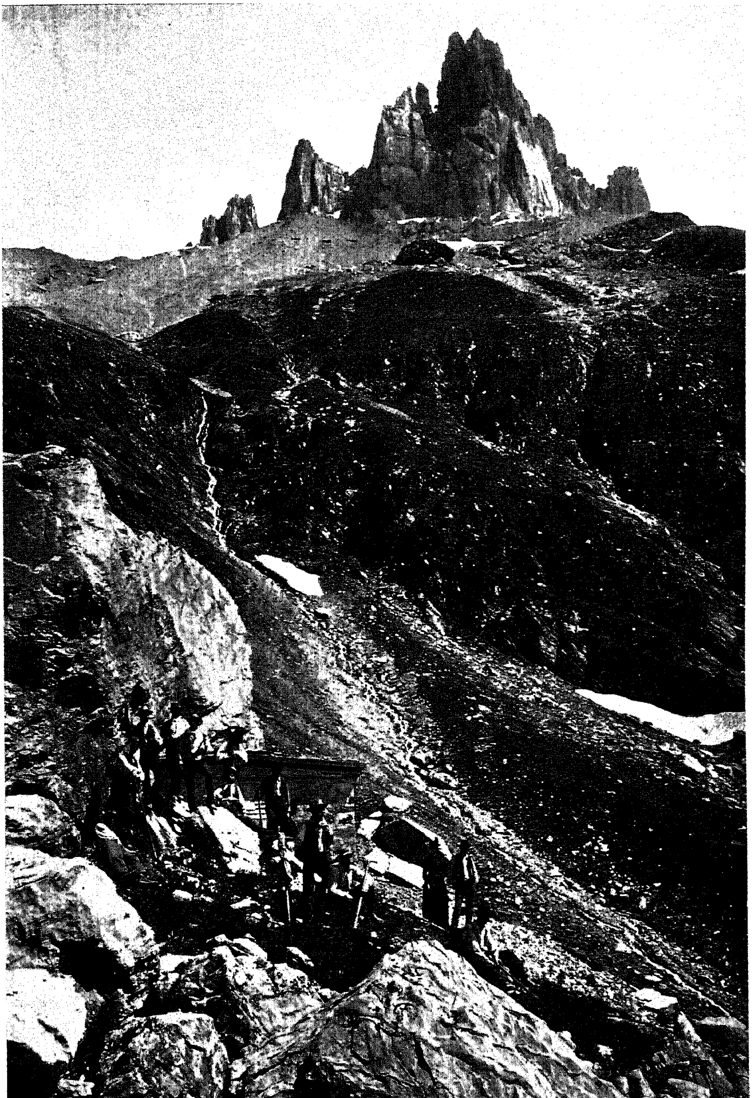
THE thick masses of sedimentary strata, partly autochthonous, partly exotic, that formerly overspread all the area presently occupied by the lofty central massifs of the Alps must have been broken up and removed at an early period. The upheaval of the fundamental crystalline rocks had lifted them into a region where subaerial waste is always carried on most actively, and their demolition must therefore have been rapidly effected. Not improbably, indeed, they may have been removed long before the massifs had reached their greatest elevation. A few relics, however, may still be seen capping the schistose rocks of the Aar massif—such, for example, as the acute peaks (Plate XXIII) of the Great Spannort (10,500 feet) and the Little Spannort (10,300 feet)

overlooking the Engelberg valley. In the same district another small outlier or remnant has been left to form the tip of the Krönte (10,200 feet), a mountain at the head of the Erstfeld valley. Although thus swept away from wide high-lying tracts, autochthonous strata and considerable fragments of exotic sheets still occupy much of north Switzerland. Needless to say the latter are quite cut off and widely parted from the regions whence they came. The Helvetian sheets that form the Limestone Alps of north-east Switzerland, for example, are separated from their "roots" by the lofty snow-clad heights of the Finsteraarhorn massif; and the Lepontine and East Alpine sheets, derived from more southern zones, are still more widely sundered from their "roots."

It is only recently that the alien or exotic character of these rock-sheets has been recognised. And now that geologists know them for what they are, certain phenomena hitherto deemed inexplicable receive a ready explanation. The occurrence in the Miocene conglomerates of many kinds of rock that could not have come from the adjacent Alps, has long been a puzzle. It was obvious that the conglomerates of the Rigi, Rossberg (Plate XXXIX), Hohe Rhonen, Gäbris, etc., were shore deposits, which could only have been derived from the denudation of mountains near at hand, but nowhere in the adjacent Limestone Alps could the source of the stones be discovered. Among them some were akin to rocks occurring in the eastern Alps, while others could only be matched in the central and southern zones of the Alpine area.

How to account for the introduction of these to the Miocene sea was the difficulty. Now that difficulty vanishes when we learn that the coast of the Miocene sea was formed by the rocks of the Lepontine and upper rock-sheets, immigrants from the central and southern Alpine zones. Only after these sheets had been removed by denudation were the underlying Helvetian sheets laid bare along the north front of the Alpine area. At the time the Miocene conglomerates were being accumulated the latter still lay deeply buried.

For over a hundred years the appearance of large erratics or wandered blocks in the Eocene "Flysch" of north Switzerland has likewise been a hard nut to crack. Some of these have a resemblance to rocks occurring in the Finsteraarhorn, while many others (*e.g.* breccias, granites, etc.) are identical with rocks that abound in the central and southern Alps. All the blocks, in short, are exotic, none being identified as native to the region where they occur. Speculation has been rife as to how they were carried. One of the latest views was that floating ice may have brought them from the south side of the Alps at a time when there was free communication across the central chain between the Eocene seas lying north and south of the Alpine area. We now know that they are simply fragments, large and small, detached from the Lepontine rock-sheets, while these were advancing across the Eocene "Flysch." It is not hard to understand how detached blocks of the kind would often be dragged or rolled for shorter or longer



THE GREAT SPANNORT, SWITZERLAND.

[Outlier of Mesozoic Strata, in the background, resting on the ancient schistose rocks of the Aar Massif.]

Photo, Wehrli, Zürich.

[*To face page* 112.

distances before they were crushed and pressed into the relatively soft Eocene deposits. Many occur sporadically, others appear in groups. Blocks 10 feet in diameter are not uncommon, but very much larger masses are occasionally met with. In the valley of Habkeren, in the Bernese Oberland, for example, one measures 105 feet in length, 90 feet in breadth, and 45 feet in height. Many blocks have their angles rounded off, and some are approximately spherical, probably the result in most cases of subsequent "weathering." For while not a few are still anchored in the "Flysch," others released by erosion lie scattered over the surface. Possibly some of these loose erratics may never have been detached as separate blocks from a parent rock-sheet at the time of its advance, but may simply be fragments derived from the gradual break-up and disintegration of the latter *in situ* long after it had become passive. They may be analogous, in short, to the "greywethers" or "sarcen-stones," so often met with in the soils of the English Chalk Downs, which are believed to be relics of certain Cainozoic beds that formerly covered broad areas in southern and south-eastern England, just as the Lepontine rock-sheets must at one time have overspread the region where the exotic or erratic blocks of north Switzerland are found.

More remarkable than these erratics of the "Flysch," however, are certain isolated hills and mountains, and even continuous ranges, which occur in the same region, and which like the erratics are of alien origin. Their exotic character is demonstrated

by the simple fact that they are "mountains without roots"; they have no genetic connection with the pavement rocks on which they rest, for the latter are much younger than the masses above them. Between the valley of the Rhine and Lake Thun, for example, and particularly in the neighbourhood of the Lake of Lucerne, there are certain prominent hills and mountains, such as the Mythen (see Plate XXIV), Mördergrube, Buochserhorn, Stanserhorn, and the Giswiler Stock (west of the Lungern See), heights of 6000 feet or more, all of which are built up of rocks quite foreign to that region. They are in fact immigrants, isolated fragments of the great Lepontine sheets of Mesozoic rocks which, during the earlier phase of the mountain-making process, were thrust forward from the south, and came to rest at last upon the much younger Eocene strata of north Switzerland. Such outlying remnants of the travelled rock-sheets or "Decken" are called by Swiss geologists "Klippen," for which we have no satisfactory equivalent in English, unless we may substitute the geographical term "drongs," as used in Shetland.[1]

[1] The English translation of Klippe, "crag, cliff, or rock," is rather indefinite, and hardly conveys the meaning of the word as used by Swiss geologists. "Stack," often applied in north-east Scotland and Scandinavian countries to isolated upstanding rocks on a sea-coast, comes nearer to the meaning. But "stack" has other significations besides that of "a pillar-like rock standing separate from a line of cliffs." The word "drongs" suggested above has only one meaning, being applied to prominent peaked rock-masses occurring in the sea at some distance from the land. It is probably an old Norse word; at all events, high sea-girt rocks lying off the coast in Iceland, the Faeroes, and Norway are often called "Drangur," *i.e.*, isolated or lonely ones.

Elsewhere in Switzerland alien rock-masses often extend continuously over considerable areas, but their true character is exposed again and again in numerous gorges, ravines, and valleys; the torrents, streams, and rivers having cut their way down through the whole thickness of migrated sheets, and laid bare the pavement of native or autochthonous strata on which they rest. When the travelled sheets, consisting of Triassic, Jurassic, and Cretaceous rocks, overlie the much younger Cainozoic strata, their alien origin is at once betrayed. In other cases both pavement rocks and superjacent sheets may be of Mesozoic age, but the former have a central European facies and obviously belong to the place where they occur, while the exotic character of the latter is shown by their Mediterranean facies.

A few words descriptive of the structure and present distribution of the several migrated rock-sheets may be added. As already mentioned, quite a number are recognised, of which the most important are the Helvetian, the Lepontine, the East Alpine, and the South Alpine or Crystalline. Each of these is a complex of several subordinate sheets, the structure or arrangement of which shows that one has moved over another. Along its terminal front (when that has escaped erosion) each sheet seems to attain a maximum thickness, and appears as an enormous recumbent fold. The major plane of movement (thrust- or sole-plane) of a complex sheet is usually more or less smoothed and striated, but the middle limb of the fold, which this plane is supposed to represent, is

often wanting, having apparently been squeezed out when it finally yielded to the *vis a tergo.* Now and again, however, an attenuated middle limb can still be followed for some distance. It is perhaps not without significance that the chief planes of movement not infrequently coincide with the Eocene "Flysch-schiefer," or with the similarly soft "Bündnerschiefer," which may have served as lubricating materials to facilitate the passage of the overriding more resistant rock-masses.

Although some of the translated rock-sheets would seem to have originated as much flattened or recumbent folds, it may be doubted whether such was often the case. The major "sole-planes" of the Alps bear a strong resemblance to the "thrust-planes" of our own north-west Highlands. Scottish geologists have shown that enormous sheets of rock, yielding to lateral pressure, have been forced one over another in successive gigantic slices, without preliminary folding. Nevertheless along the terminal front of such a great rock-slice overfolding is sometimes conspicuous. Not improbably, as already indicated, this structure may have been developed by friction at the base of an advancing sheet, the resistance to movement having caused the brow of the latter to curve and curl over, and so to become inverted and infolded to a less or greater extent under the sheet itself (see Fig. 31). It thus seems not unlikely that such may be the origin in many cases of the overfolding and consequent thickening of the Alpine "Decken," which are so characteristic of their terminal fronts.

One cannot, in short, help suspecting that it has been too often taken for granted that each sole-plane in the Alps represents the middle limb of an enormous recumbent fold, drawn out till it thinned away, and was subsequently replaced by a fault or horizontal displacement. The fact that such sole-planes so frequently coincide with the least resisting strata would seem to indicate that these last were planes of weakness or minimum resistance along which the rock-masses yielded most readily to lateral thrust.

Although geologists who have made a special study of the Alps are agreed as to the translation from south to north of vast rock-sheets, there are still many enigmatical phenomena connected with the genesis and movement of the immigrating masses which future research must be left to explain. It is very difficult to picture to ourselves the conditions that may have obtained while one rock-sheet was advancing over another. Before the earliest sheet began to move forward it is probable, as we have seen, that lateral compression had succeeded in causing the entire Alpine area to bulge upward. A broad swelling or "geanticline," with perhaps subordinate undulations of the crust, may have come into existence, and extended in a general east-and-west direction along the middle zone of the region. With continued pressure more or less pronounced folding would doubtless be developed at some depth within the geanticline. Compression increasing, many folds would by and by become inverted and overthrusts would be produced, or great slices would be driven

forward without preliminary folding. Upon the southern slopes of the geanticline each ruptured fold or detached sheet would travel up a gentle incline, until the crown of the primeval swelling was attained. Thereafter the sheets, one following another, would begin to descend the northern slopes of the great bulge, which may or may not have been inclined at a greater angle than the southern slopes. Some geologists have suggested that the successive piling of one sheet upon another, and possibly also a synchronous elevation of the geanticline, may have combined to render the descent to the north so steep as to induce the wholesale gliding of the travelled masses, sheet after sheet, under the influence of gravity, "flowing" downwards and burying its brow in the soft Eocene strata of the foreland. Those who hold this view assume that a broad and deep depression must have extended along the base of the geanticline, in order to accommodate the enormous rock-masses descending from its crown. By the descent of these masses, which now form the lofty border ranges of the Alps, extending from Säntis to the Diablerets, the depression was filled up, and at a subsequent date the entire region became elevated. Whether or not these views may approximate to the truth we do not know; they are at present purely conjectural.

Owing to the extraordinary denudation of the Alps, it will readily be believed that the several travelled rock-sheets are now in a very tattered condition. The Helvetian, whose "roots" are said to appear in the Vorder Rhine and the Rhone

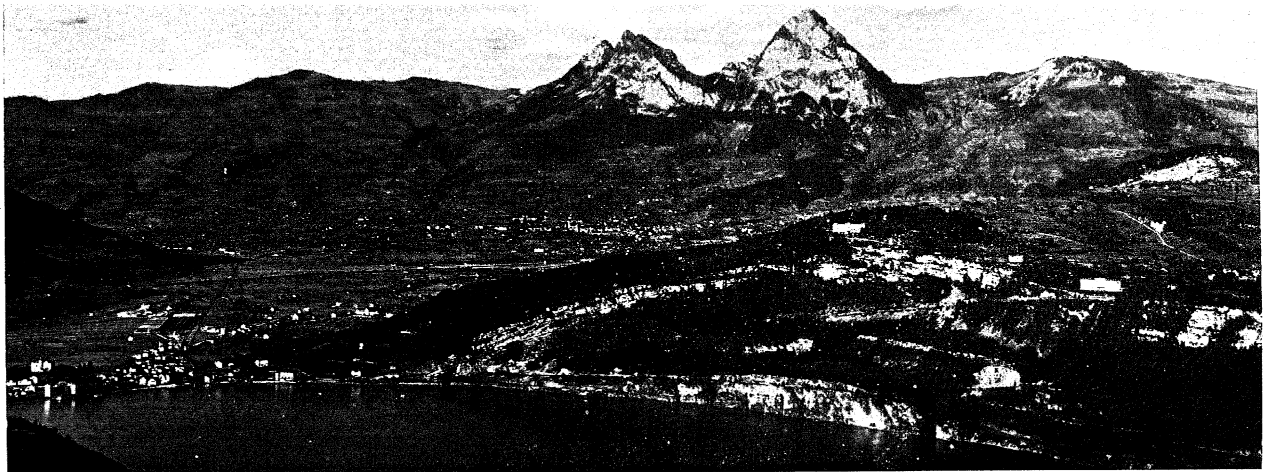
valleys, has been cleared away from the Aar massif, but puts in a strong appearance north of that massif, where it constitutes the border ranges of the Limestone Alps, stretching from Säntis and Churfirsten south-west to the Lake of Lucerne, Lake Thun, and the Diablerets. The Lepontine, the "roots" of which have been detected chiefly south of the Gotthard, formerly covered the Helvetian extensively, but has since vanished from wide areas. Its most conspicuous remnants in north Switzerland form the "Voralps" of Chablais and the Stockhorn, and the pre-Alps of the Bernese Oberland up to the foot of the Diablerets and the Wildstrubel. East of the Lake of Thun it is represented by the Klippen or Drongs already described. Its most extensive exposure, however, occurs further south, and comprises the mountains of Graubünden that border on the Vorder Rhine, the Alps of Valais, the Graian Alps, etc. Overlaid on the south by the East Alpine sheet, it continues eastward under that sheet for an unknown distance. Its prolongation in that direction, however, is proved by the notable fact that in Lower Engadine it peers through a great aperture, or "window" as it is called, in the overlying East Alpine sheet. That "window" opens on the back of an anticlinal ridge which, if it existed before the advance of the East Alpine sheet, might possibly have caused strain and tension in the overriding rock-mass, and so brought about its rupture. On the other hand, the anticlinal fold may belong to the later phase of crust-movement, for, as we have seen, much of the

most profound folding of the exotic rock-sheets was effected after these had become passive. The "window," therefore, may not represent a rent formed during the movement of the rock-sheet in which it occurs. It is just as likely to be the result of long-subsequent denudation, the removal of material from the back of an anticline being of common occurrence everywhere. In the region of the Hohe Tauern a similar but much larger "window" has been opened in the same far-spreading sheet, through which look out the Lepontine masses of the Gross Glockner and its giant associates (see Map, Fig. 32).

The South Alpine sheet occurs furthest south, and consists chiefly of a complex of old crystalline rocks which have been driven forward from the southern margin of the Alpine area. This sheet appears to have formerly extended over wide tracts of the central region, from which it has since been largely removed by denudation. One considerable remnant is the great cake of gneiss that spreads from south-west to north-east across the central Alps from Mont Emilius to the Weisshorn. Some of the more prominent peaks developed by denudation in the sheet are the Matterhorn, Dent Blanche, Gabelhorn, Zinal Rothorn, Weisshorn, etc.—mountains without roots, therefore, which have travelled some thirty or forty miles from the place of their origin in Piedmont (see Plate XXV).

And here we may note a certain rather marked contrast between the ancient crystalline rocks of the northern and southern zones of the Alps. The

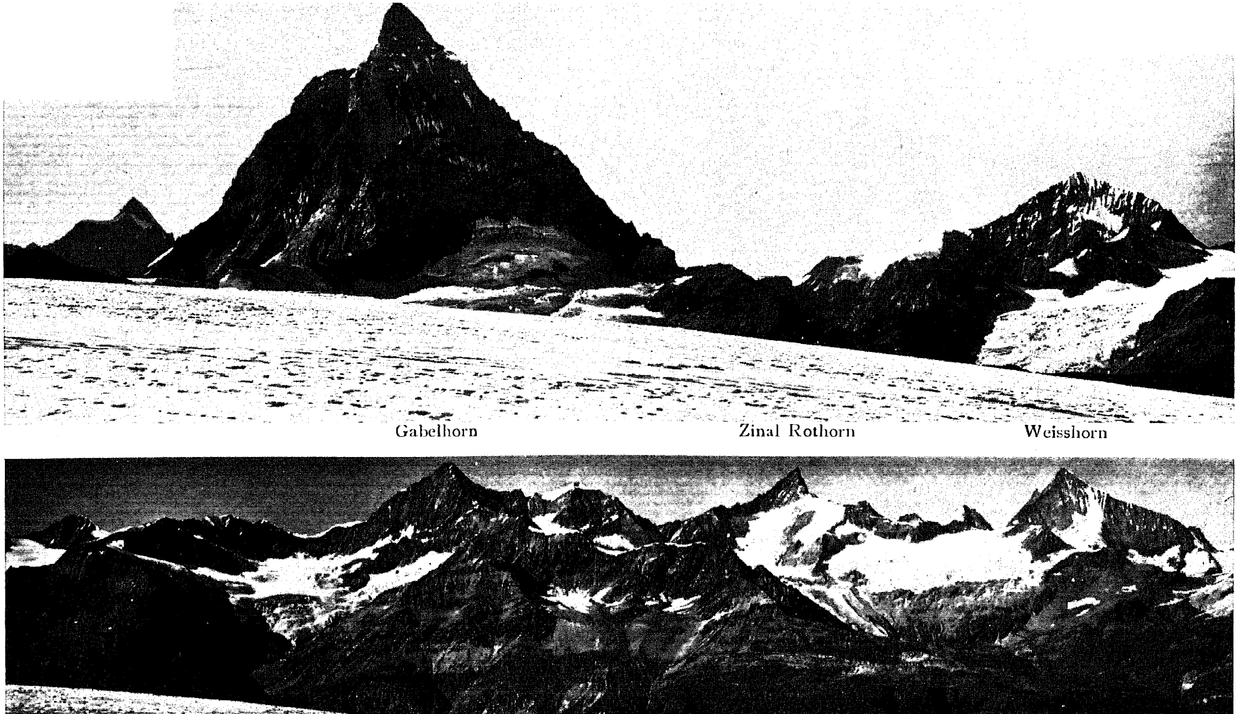
PLATE XXIV.



THE MYTHEN AND ROTE FLUH, OVERLOOKING SCHWYZ, SWITZERLAND.
[Mountains without "roots"; composed of Mesozoic strata resting upon the Eocene Flysch.]
Photo, Wehrli, Zürich.

Matterhorn

Dent Blanche



PANORAMA FROM THE THEODULE HUT.

All the mountains named are without "roots"; they consist of ancient Gneiss (*a*) which rests upon Mesozoic strata—(*b* = Trias; *c* = Bündnerschiefer).

Photo, Wehrli, Zürich.

[Between pages 120 and 121.

massifs of Mont Blanc, the Aiguilles Rouges, Aar, and Gotthard were highly compressed, and to some extent sharply interfolded with the younger stratified rocks that formerly covered them; but none of these folds developed into extensive displacements, nor were any great slices forced from the massifs and pushed forward as rock-sheets. It was quite otherwise, however, with the corresponding rocks of the southern zone, immense sheets of the old crystalline masses having been thrust for many miles over rocks younger than themselves.

From the foregoing brief account of the essential characters of Alpine architecture, it may be gathered that the occurrence of older overlying younger rocks is much the most notable. "Inversion," as it is termed, is the outstanding feature in the structure of the mountains. Although the full meaning of this structure has only been realised within recent years, the fact that inversion did occur has long been known, and even to some extent correctly interpreted. Recumbent anticlines and inverted strata were observed many years ago in the Alps and other regions of mountain uplift. Professor Heim, in his classical work on the mechanism of mountain formation,[1] gave an admirable description of the remarkable rock-structures met with in the Tödi-Windgällen group, and showed by means of maps and excellent profile sections how large a part was played by inversion in the architecture of that region. So

[1] *Untersuchungen über den Mechanismus der Gebirgsbildung, etc.*, 1878.

clearly is the evidence set forth in this masterly monograph that the author's explanation of the perplexing structures was for a long time accepted as satisfactory. There were certain phenomena connected with the great overfolds, however, for which it was hard to account. In a simple overfold the rock-movement has obviously been in one direction; if the crown or brow of a recumbent anticline faces north, the thrust must obviously have come from the south. But in the Glarner region the structures were apparently inexplicable, save on the assumption that here we had to do with two overturned and flattened anticlinal folds approaching each other from opposite directions, the crown or brow of the one looking north and facing that of the other which looked south. This structure, surmised long ago by Escher v. der Linth, was described by Heim as a "double-fold," the two recumbent anticlines enclosing between them a great synclinal trough of much disturbed and convoluted strata. There was no direct evidence, however, for the existence of the two recumbent anticlines—their crowns could nowhere be seen. A glance at Heim's section (A, Fig. 34) shows, indeed, that the supposed "double-fold" is quite hypothetical, for he represents the anticlines by dotted lines. B (Fig. 34) is a section across the same region, with the late Professor M. Bertrand's interpretation of the structure, indicated, as in Heim's section, by dotted lines. According to the explanation given by Escher and Heim, it would seem as if crustal movement had taken place in diametrically

opposite directions; the later interpretation, however, shows that movement has been in one direction

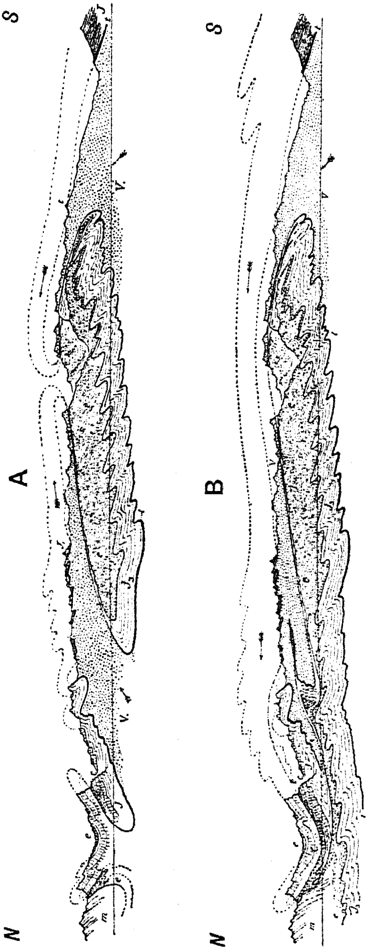


FIG. 34.—Schematic Sections of the Folded Strata of the Glarner Region.
A, The Glarner "Double-fold" according to Escher and Heim (1870-1902).
B, The Glarner "Rock-sheet" according to Bertrand (1883), Suess (1892), Heim (1903).
m, Molasse (Nagelfluh); *e*, Flysch; *c*, Cretaceous strata; J, Jurassic strata; *t*, Helvetian Trias; V, Verrucano (Permian conglomerates). (From Heim's *Der Bau der Schweizeralpen*.)

only—one great rock-sheet has been thrust forward from south to north over the whole region.

In the same district (see north end of section A,

Fig. 34), and elsewhere, another puzzling structure presented itself which was equally difficult to understand, but which Heim explained much in the same way as he did the Glärnisch inversion. According to him the structure in question was an example of a so-called "mushroom fold" (Fig. 35, A). In this

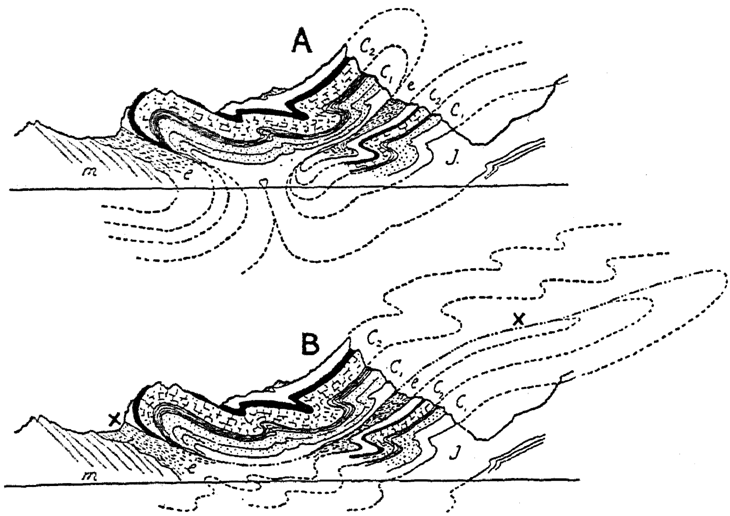


FIG. 35.—Schematic Interpretations of Folded Strata.

A, A Mushroom Fold, showing two steeply-inclined synclinal folds approaching each other under two corresponding overturned anticlinal folds.

B, An Overfold, which has yielded to compression along the thrust-plane x x.

J, Jurassic strata; C_1 C_2, Cretaceous strata; *e e*, Flysch; *m*, Molasse. (From Heim's *Der Bau der Schweizeralpen.*)

fold two synclinal troughs lying at a steep angle were supposed to approach each other—the strata in each syncline dipping underneath two corresponding overturned anticlines—the crowns of which looked away from each other in opposite directions. The supposed structure was, in short, like that of a "double fold" turned upside down. In point of fact, however, only

one anticline could be actually seen, and its crown faced the north; the other anticline was nowhere visible. Like the anticlines of the so-called "double fold," the latter was entirely hypothetical, as indeed is indicated by the dotted lines in the section (A). What is believed to be the true structure, Professor Heim illustrates by means of the section (B), which shows a faulted recumbent overfold.

Both "double fold" and "mushroom fold" implied movements of the crust in diametrically opposite directions. On a limited scale contradictory movements of the kind might quite well occur in consequence of a thrust in one direction. A broad and thick sheet of rocks driven forward, say from south to north, might, under certain conditions, be overfolded in some place or places towards the south. If, for example, the supposed movement northward were interrupted by some abrupt obstacle, a certain amount of back-folding might be expected to take place immediately in front of the obstacle. The back-folding, however, would be only of local occurrence and on a relatively small scale. But one cannot believe that inversion on so large a scale as that of the Glarner could have been the result of back-folding, caused by the heaping-up and buckling of the strata against a steadfast obstacle.[1] If the

[1] It must not be supposed, however, that all the larger folds of the Alps lean over persistently towards the north, *i.e.*, in the general direction of the crustal movement. Back-folding on a limited scale occurs here and there, while in certain areas, as in the Limestone Alps of north Italy, the crowns of the anticlines most frequently face southwards.

"double-fold" existed it could only have been formed by two independent movements, one in a direction opposite to the other. And similar contradictory movements would be required to explain the formation of a "mushroom fold."

Apart from such considerations it had always been difficult, on the hypothesis of a "double fold," to account for the sudden pinching out of an immense thickness of strata between the crowns of two closely confronted recumbent anticlines. Compression might explain an apparent considerable reduction in the thickness of the strata, but could hardly be responsible for the disappearance of hundreds or even thousands of feet of rock. And so again in the case of a "mushroom fold," the strata on either side dipped at so high an angle that the "stalk of the mushroom" must either be inconceivably attenuated or squeezed out altogether. In short, there was no room underneath for the accommodation of the folded rocks. In this case, as in that of the "double fold," an enormous mass of rock must have unaccountably vanished.

But according to MM. Bertrand, Lugeon, Schardt, Schmidt, Steinmann, Termier, and indeed all recent observers, no extensive recumbent double folds, either anticlinal or synclinal, occur anywhere in the Alps. The great inversions are everywhere explained by overfolding and horizontal movement in one general direction, and on a much grander scale than even Heim had suspected. The last-named geologist is now of the same opinion himself, and has

of late years adduced much additional evidence in support of the new doctrine. No one, indeed, has stated the facts and set forth their interpretation more clearly. Not only has he frankly abandoned his old views, but by newer researches he has endeavoured to show that the conception of Alpine structure outlined by the late Marcel Bertrand is applicable to every part of the great chain which has been critically examined.

The recognition of this dominant structure has explained much in the geology of the Alps which had hitherto perplexed the keenest observers. Palæontologists, for example, had been puzzled by the remarkable sequence of strata which they encountered when the mountains were traversed at right angles to their axes. Thus they might find certain strata which, from their nature and the character of their fossils, had obviously been accumulated in deep water, succeeded immediately by another series of beds which were just as obviously the products of deposition in shallow water. In a word, the lithological character of the rocks and the facies of the fossil faunas changed too abruptly, deep-sea and shallow-water accumulations were unnaturally associated. It was otherwise when the strata were followed along their outcrops in the direction of the axis of the chain. In that direction there was no sudden passage from beach to deep sea. On the contrary, the assemblage of fossils belonging to any particular zone of rocks remained unchanged for great distances, such modifications as did occur taking place quite gradually.

Another phenomenon that seemed inexplicable was the abrupt disappearance of thick masses of some distinctive kind of rock, such as marine limestone, which, as a rule, usually extends over very wide areas and only gradually thins away. Geologists were, of course, well aware of the fact that individual beds and groups of beds often thicken out or thin off irregularly. A series of coarse sandstones, for example, may be 200 or 300 feet thick in one place, and yet die off within a mile. Such phenomena, however, are quite in keeping with existing conditions of sedimentation. In our present seas there is usually a gradual transition from shallow to deep water. But throughout the littoral zone gravel and sand rapidly alternate; there is, in short, a constant interosculation, a thickening out and thinning off of lenticular sheets of gravel, grit, and sand. Below the littoral zone the deposits are finer grained and slowly accumulated, and tend to spread in more or less extensive sheets over wider areas. Marine limestones, which are calcareous formations of organic origin, accrete more slowly still, and usually in clear and somewhat deep water. They may therefore be expected to cover very broad areas of the sea-floor. It was consequently perplexing to find that in the Alps, a mass of limestone 2000 feet in thickness could be followed sometimes for only a few miles.

All these and many similarly bewildering phenomena are readily understood, since we have learned that the sequence of strata encountered when the

Alps are traversed from north to south is the result of overfolding and horizontal displacements, whereby beds which originally lay far apart have been brought together. Strata with a Mediterranean facies have come to rest directly upon rocks, the facies of which is just as distinctly central European. Deep-sea deposits have been pushed out of place and now overlie accumulations of shallow-water origin, or *vice versa;* while the abrupt disappearance of thick limestones points to the irregular overlapping of one displaced rock-sheet by another. When it is understood that some of these overlapping sheets have travelled from the centre and others from the southern zones of the Alps for distances of thirty or even of sixty miles, no surprise need be felt that geologists were, for a long time, baffled to account for the apparent succession or sequence of the strata.

The views entertained by Swiss geologists as to the structure of the Alps have recently been called in question by Mr Bailey Willis, the well-known American geologist. Mr Willis fully admits the importance and extent of overthrusting in the structure of mountain chains, and particularly of the Alps. He does not doubt that the latter consist chiefly of overthrust masses, neither does he question the amount of displacement. He differs, however, from Swiss geologists as to the mechanics of overthrusts. The flattened and greatly extended recumbent folds with their "roots," he thinks, are impossible structures, the translated rock-sheets

being, according to him, displacements of the same character as those of the Scottish Highlands. Moreover, he adduces evidence to show that crustal movement has not always been in one and the same direction, as Swiss geologists have maintained. He recognises two separate movements: an earlier one, when overthrusting took place from north-west to south-east; and a later one, when rock-masses were driven forward in the opposite direction, that is from south-east to north-west. He regards it, therefore, "as probable that the recognition of intersecting overthrusts and of systems of major and minor thrusts of the Scottish type, combined with unusual but incidental folding, will eventually be found to explain a large part of Alpine structures."[1]

While overfolding and wholesale horizontal displacements are the most characteristic features of Alpine architecture, it must not be forgotten that compression resulted also in the bulging up or general elevation of the great central massifs, and in diminishing the width of the entire Alpine area. Many years ago Professor Heim was of opinion that if all the Alpine folds were smoothed out and the strata regained their original position, they would necessarily extend over a much wider area; the two points, Zürich and Como, for example, would be further apart than they are at present by some 120 to 150 kilometres. But this estimate he now thinks is much under the mark; according to him, the Alpine area before compression took

[1] See *Smithsonian Miscellaneous Collections*, vol. lvi., No. 31 (1912).

place was a flat land measuring probably 600 to 1200 kilometres across. Instead of this broad low-lying tract, we have now a lofty mountain chain averaging no more than 150 kilometres in width.

CHAPTER VII

ORIGINAL OR TECTONIC MOUNTAINS—*continued*

Denudation of the Alps. Relation of Surface to Internal Structure. Rivers Older than the Ranges they traverse. The Cycle of Erosion. Forms of Mountains assumed under Denudation: Influence of Chemical Composition and State of Aggregation of Rocks, Bedding-planes, Joints, etc. Schistose and Igneous Rocks, their Lines of Weakness. Origin of Jointed Structures.

In the preceding chapters some reference has been made to the denudation of folded mountains. The most cursory examination suffices to show that the form or configuration of the Alps seldom or never coincides with their geological structure; the irregularities of the surface rarely appear to be the direct expression of the rock-arrangements underneath. Here and there some approximation to an agreement of the kind may be discerned, but even in such cases it is quite obvious that the actual surface is not original, but the result of denudation. Such enormous quantities of material, in fact, have been removed from the Alpine area, that many geologists do not doubt that the mountain masses that remain bear only a small proportion to those which have gradually been carried away.

The uplift of the Alps commenced, as we have seen, in Eocene times, was continued all through the Oligocene and Miocene, and practically completed at or about the beginning of the subsequent Pliocene period.[1] Equilibrium and repose may have been attained somewhat earlier in the southern than in the northern zone, but this cannot be demonstrated. All we know is, that the existing valley-system of the southern Alps had come into existence before Pliocene times, so that when subsidence ensued during that period the great valleys on the south side of the chain became sea-lochs. As no marine deposits of Pliocene age occur anywhere on the north side of the chain, we cannot be sure that the valley-system of the Swiss Alps was as well developed in Pliocene times as that of the Italian Alps. On the other hand, there is no evidence that would lead us to believe otherwise. The probabilities are that the two sides of the chain bore much the same relationship to each other then as they do now; in a word, it is most likely that the development of their several drainage-systems proceeded *pari passu*.

Denudation must have commenced with the first appearance of the Alpine area as dry land, and doubtless continued without pause throughout the whole period of mountain growth. Thus, long before the final phase of crustal compression had been inaugu-

[1] This statement must not be taken too literally. Some minor deformation appears to have supervened in Pleistocene times, and it is quite possible that the frequent tremors and earthquakes which still affect the Alpine area may be an indication that crustal movement has not yet finally ceased.

rated, a prodigious amount of erosion must have been effected. The Miocene molasse, with its great masses of shingle, gravel, and sand, is sufficient evidence of that. And if denudation was in active progress during the first phase of crustal deformation, we may feel sure that the final phase was in like manner accompanied throughout by never-ceasing erosion.

What the direction of its drainage-system may have been when the Alpine area appeared above the level of the Eocene sea can only be conjectured. The land probably at first showed a somewhat level or flat surface. Even at that incipient stage, however, there may have been a slight axial bulge sufficient to form an east-and-west or a north-east and south-west watershed. If that were so, then transverse streams and rivers would be the earliest to appear. When the crustal movement had been in progress for some time, the larger longitudinal folds must have wrinkled the surface and influenced the drainage. It is not improbable, therefore, that at a very early stage in the development of the Alps, both transverse and longitudinal rivers had come into existence.

When we are speculating on the effect produced at the surface by crustal deformation, we must remember that the complicated rock-structures everywhere conspicuous in the Alps originated under an enormous thickness of strata. Flexures and folds of the kind could therefore have had only a moderate influence on the configuration of the surface. No doubt deep-seated rocks must frequently have snapped under stress and strain, causing tremors, jarrings, and

earthquakes, so that rock-falls and landslips at the surface may often have occurred, and brought about multiform local modifications of the drainage. It is highly probable, moreover, that crustal compression may again and again have expressed itself at the surface by elevations of a more or less pronounced kind, which would bring into existence many younger streams and rivers. There is no evidence, however, to suggest that the subterranean processes referred to ever resulted in wholesale revolution of the Alpine drainage-system. It is hardly credible that rock-sheets, thousands of feet in thickness and hundreds of square miles in extent, were driven forward rapidly, or that they slipped down slopes after the manner of avalanches. Had catastrophic movements of the kind occurred, some evidence of them should be forthcoming. But so far as can be judged from the present disposition of their drainage-system, the Alps do not seem to have experienced any such strange revolutions at the surface. The directions of the more important rivers were probably determined at an early date, the leading features of the whole system of drainage having been roughly outlined long before the land had attained any considerable elevation. The modifications it has since undergone are due doubtless partly to deformation of the surface by crustal compression, whereby new water-courses have come into existence and entered into competition with their predecessors. Many modifications of the drainage, however, must be attributed to the erosive action of the rivers them-

selves, influenced by the nature of the rocks and rock-structures they have encountered while deepening and widening their valleys.

During the last phase of crustal movement the configuration of the surface along the northern border of the Alps appears to have been more or less strongly affected. To that phase belong the folds of the Säntis and the Jura, which betray their youth by the fact that they have experienced less erosion than other parts of the Alpine area. The comparatively well-conserved character of these and many other young mountains of upheaval, demonstrates that deformation of the surface by crustal movement proceeds more rapidly than general atmospheric denudation. Obviously this must be so, or the formation of tectonic mountains of the kind would be an impossibility. They would be degraded as fast as they grew. Nevertheless so potent are the agents of erosion that they have succeeded in greatly modifying even the youngest elevations of the land.

Although no portion of a growing mountain range can escape such modifying influence, it is evident that the process of waste must be carried on most actively along lines of water-flow. As torrents, streams, and rivers cut their way down into an uprising massif, larger and larger surfaces of rock become exposed to subaerial action. The shattered debris detached from cliff and mountain slope, slowly or more rapidly enters the drainage-system, gradually becomes reduced, and eventually is swept away as gravel, sand, and mud beyond the limits of the mountain area. In

this manner profound and broad valleys are excavated, and these continue to be deepened and widened all the time that mountain-making goes on. In short, the rate of erosion keeps pace with or may even exceed the rate of rock-folding and uplift, and thus mountain range after mountain range may be successively sawn across by the primary rivers of a region undergoing crustal compression. The Indus, for example, has neither been dammed back nor deflected by the secondary and more recently formed ranges of the Himalaya, but has cut its course down through these mountains as fast as they rose. The same phenomenon confronts us in north Switzerland, where the Rhine traverses the young Helvetian folds on its way to the Lake of Constance. While folded mountains, therefore, cannot be developed across the valleys of active rivers, their growth outside of these valleys is not prevented by other epigene agents of erosion, however much the latter may modify their configuration.

The valley system of the Alps has no doubt in the course of ages become more and more complex. The protracted process of crustal deformation must from time to time have brought new streams and rivers into existence, and these would forthwith enter into competition, so to say, with others of earlier origin. Probably many rivers may at first have followed transverse or longitudinal courses more continuously than they do now. At present we see one and the same river running sometimes in a transverse, sometimes in a longitudinal direction. It is quite possible

that erratic courses of the kind may sometimes have been determined by deformation of the surface, but in many cases they are probably due to the action of the rivers themselves. Some streams, owing to various circumstances, such as steeper gradient and larger volume, are more energetic workers than others in their vicinity. A transverse stream, for example, may cut its way back towards its water parting, and eventually breach the ridge in which it rises, and thus open a way into a longitudinal valley occupying a higher level. The river in the latter may consequently be captured and diverted into a transverse course. Many captures of the kind have been effected throughout the Alpine lands, and not improbably most of the erratic courses pursued by the streams and rivers have originated in such ways. To the action of the streams must be added that of the enormous glaciers of the Ice Age, which partly by profound erosion and partly by accumulation of morainic and fluvio-glacial materials, have produced many remarkable changes in the drainage-system of the Alps. But the further consideration of this subject is beyond the purpose of these pages. The history of the evolution of Alpine valleys would require a volume to itself to do it justice. At present all that we are concerned with is the general denudation of the region.

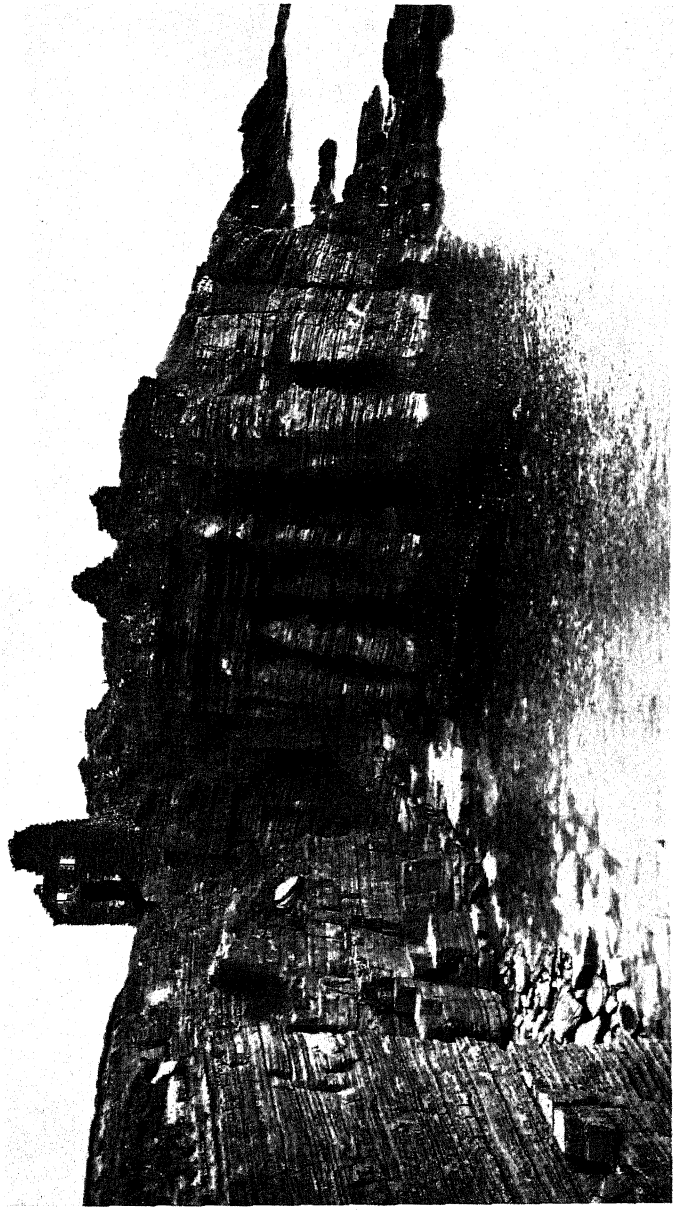
When it is recognised that the existing mountains represent only a fourth or a fifth part of the original land mass, it needs but little imagination to conceive of a time when the entire region must be reduced to

its base-level. Should no renewed crustal compression supervene, all that vast array of stupendous heights must gradually crumble down, and be ultimately replaced by a gently undulating plain. The process of decay, everywhere conspicuous, will go on apace until, with the gradual lowering of the surface the rate of waste will diminish, but nevertheless degradation will never cease. The rivers and their multitudinous affluents must continue to deepen and widen their valleys, and to cut back into their watersheds, and thus the mountain ridges that separate the valleys will gradually lose in height and width. All the beautiful lakes will disappear at an early stage. At present they form the base-levels of the drainage-areas in which they lie; they are the receptacles of the waste materials of the mountains, and must be relatively soon silted up. Thereafter the detritus of the Alps will make its way by the great rivers to the sea, which will then have become the base-level. Slowly but surely the plain tracks of rivers and streams will travel up the valleys, slowly but surely the heights of the land must be reduced, until the entire Alpine area is finally resolved into a rolling plain. The cycle of erosion will then be completed.

But the geological history of other mountains, and of the Alps themselves, teaches us that a cycle of erosion may be interrupted by crustal movement. The present Alps, it will be remembered, were preceded in Palæozoic times by an extensive mountain land, which after a prolonged period of denudation sank in the sea, before it had been completely reduced,

and remained submerged during the course of long ages. In other cases a mountain tract, after experiencing much erosion, has again been uplifted, and its final demolition has thus been deferred. But with renewed upheaval denudation proceeds more rapidly, for the rivers with their increased gradients regain their former greater activity, and if the uplift has been considerable the action of ice may be added to that of running water. The lowering of the land continues, and will not cease, even should occasional uplifts recur, until the region is either submerged or worn down to its base-level. In a later chapter we shall refer to certain vanished mountain chains which are now represented by plains and plateaus. For the present, however, we may take a rapid glance at some of the varied forms attained by the Alpine heights under the influence of denudation.

It will be readily understood that, owing to differences of composition, rocks must break-up and crumble-down in various ways and at different rates. A limestone, for example, consists of material (carbonate of lime) which is soluble in rain-water. In time, therefore, such a rock is gradually carried away in solution as a bicarbonate, leaving behind it any insoluble ingredients it may have contained. On the other hand, a quartz-rock, composed essentially of insoluble silica, resists the chemical action of rain. Between these two extremes comes a vast variety of rocks, hardly any two of which yield to that action in quite the same way. According to the nature of their mineral constituents some are decomposed with ease,



FLAGSTONES TRAVERSED BY TWO SETS OF JOINTS AT RIGHT ANGLES TO EACH OTHER, BUCHOLLIE CASTLE, CAITHNESS.

Photo, H.M. Geological Survey.

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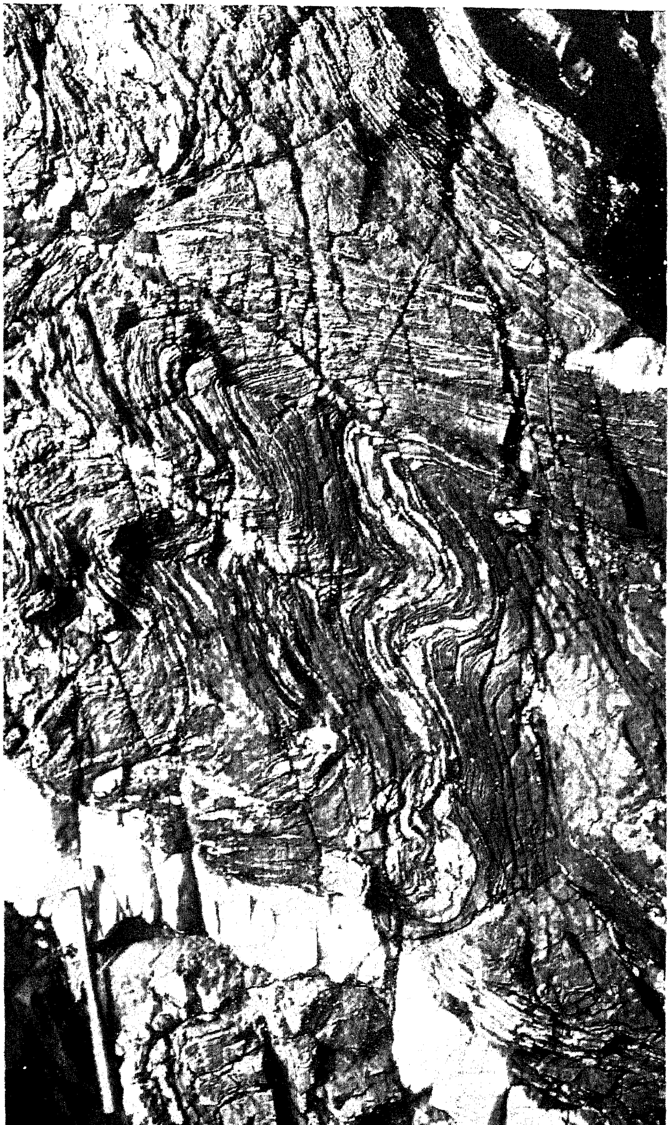
while others are only very slowly affected. Rock-disintegration, however, is influenced not only by the composition of the mineral constituents but by their state of aggregation. A porous rock, for example, is readily permeable, and therefore more amenable to the chemical action of rain than a less permeable variety of the same kind of rock. It need hardly be added that loosely consolidated masses, no matter what their composition may be, must succumb to the mechanical action of rain and frost much more readily than firmly consolidated rocks composed of similar ingredients.

But the forms assumed by mountains under the influence of denudation are determined, not so much by the chemical composition and state of aggregation of the rocks, as by the character and particular disposition of their division-planes. For, viewed in the mass, rocks are not so sound and free from flaws as in hand specimens they might seem to be. On the contrary they are traversed in different directions by regular or irregular planes, abundant or not as the case may be, along which they tend to separate. Rain, therefore, acts not only superficially but, finding its way by such fissures into the heart of a mountain, it may bring about the alteration and decay of rock-constituents at very considerable depths from the surface. But however important in certain respects such chemical changes may be, they cannot compare with the results brought about by the mechanical action of water when it freezes. Frost wedges fissured rocks asunder, and consequently produces

enormous havoc. It is thus that mountain-summits often become buried in their own ruins, while the prodigious sheets of angular debris which curtain steep slopes, or gather at the base of cliff and precipice, must convince us that the wastage of a mountain by the agency of frost is far in excess of anything caused by the chemical action of percolating rain.

It must not be supposed that frost is the only mechanical agent that plays its part in the reduction of mountains. Running water undoubtedly is also a most effective agent. Torrents, as everyone knows, plough out gorges and ravines on mountain-slopes, showing quite clearly that when the action of water is concentrated, its work of demolition may surpass that of frost. The rocks cut into are often undermined, and the overhanging masses tend to break away along cracks and fissures. But in point of fact the erosive work of torrents is greatly aided by frost, so that in all places where the latter is experienced, the two agents play into each other's hands. There are, of course, other causes of rock-disintegration and disruption, but in such a region as the Alps running water and frost are by far the most potent. And as the natural division-planes by which all rocks are traversed are lines of weakness along which they are most readily attacked, it is obvious that the forms assumed by mountains under denudation must be largely determined by the character and arrangement of those division-planes. It may be useful,



CONTORTED SCHISTS, WITH QUARTZ VEIN, MUCHALS CAVES, KINCARDINESHIRE.

Photo, H.M. Geological Survey.

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therefore, to consider briefly how rocks come to be thus divided.

Two kinds of division-planes are readily recognised, namely, (*a*) *bedding-planes*, and (*b*) *joint-planes*. As might have been expected, a bedded structure is most characteristic of aqueous rocks (Plate XXVI). These have been spread out and accumulated in lakes and estuaries, or on the floor of the sea, as sediments of one kind or another. Each individual bed may attain a slight or a very great thickness. It may be fine-grained or coarse-grained. The finest kind of sediment is most frequently arranged in thin, leaf-like layers, such as common argillaceous shale, a structure indicative of gradual accretion. Even coarser grained deposits, such as sandstone and conglomerate, frequently show similar evidence of gradual accumulation, the beds often consisting of lenticular layers of finer and coarser ingredients, alternating more or less rapidly one with the other. In other cases evidence of gradual accretion may be inconspicuous or apparently wanting, as in freestones and many limestones. But even such fine-grained and seemingly structureless rocks are most readily divided in one particular direction, their rift or grain coinciding, like the lamination of shales, with the plane of accumulation. It goes without saying, however, that the most strongly marked planes of division in stratified rocks are those which separate one bed from another. It is rather along such planes, therefore, than planes of lamination that strata are most readily assailed by the agents of denudation.

Schistose rocks often simulate closely the laminated structure of many aqueous or sedimentary rocks. And like these they exhibit bedding, one kind of schist being more or less sharply separated from immediately overlying and underlying metamorphic rocks. But such division-planes are generally much less regular than the bedding-planes of sedimentary strata, while the planes of foliation are often so obscure, as in coarsely crystalline gneiss, that the rock might readily be mistaken for a massive granite. Moreover, schistose rocks of all kinds have usually been much disturbed, so that planes of bedding and foliation alike are often confusedly folded, contorted, and crumpled (Plate XXVII).

Igneous rocks may occur as amorphous masses of unknown but great thickness, and wholly devoid of any bedded structure. Often, however, they appear in the form of sheets or sills (Plate XXVIII), and dykes which have been intruded amongst pre-existing strata. In many other cases they are obviously true lavas with accompanying beds of tuff. Bedding-planes necessarily occur in such a volcanic series, but they are not so characteristic of igneous rocks generally as they are of aqueous strata or even of schists.

Joint-planes traverse every kind of rock, whether aqueous, igneous, or metamorphic. Aqueous rocks are commonly cut across by two sets or series of joints, disposed at approximately right angles to each other and the planes of bedding. The usual

PLATE XXVIII.

COLUMNAR JOINTING IN SILL, DRUMADOON, ARRAN. [Quartz-porphyry intruded among Triassic strata.]

Photo, H.M. Geological Survey.

[*To face page* 145.

arrangement of these joints, and their relation to the bedding of the strata, are well shown in Plate XXVI. When strata, therefore, are thus regularly jointed they tend to separate into rudely rectangular, quadrangular, or cuboidal blocks. Now and again, however, only one set of joints may appear, while the intervals between separate joints is more often than otherwise very variable. In some cases the joints may be very close together; in other cases they may be many feet or yards apart. Normal joints, as these may be called, are frequently accompanied by others running in any direction, but always more or less steeply-inclined or approximately perpendicular to the bedding-planes.

Schistose rocks are likewise divided by joints, but these seldom or never exhibit the regularity characteristic of the corresponding fissures in aqueous strata. On the contrary they ramify and straggle in all directions, traversing planes of foliation usually at high angles, and often so abundantly that it may be hard to detach a sound fragment of the rock more than a few inches across. Not less frequently, however, they are wider apart, and may thus enclose irregular-shaped blocks, slabs, and reefs, several feet or yards in diameter. It is usually among the gneisses that the nearest approach to something like a definite system of joints may be observed. Thus two sets of joints may cut each other and the rude bedding-planes at approximately right angles, and the rock in this way becomes divided up into rectangular or roughly quadrangular and cuboidal blocks.

The jointing of igneous rocks, like that of schists, is often confused, particularly in the case of great amorphous masses. Now and again, however, granites and granitoid rocks are divided by approximately regular systems of joints, two vertical sets cutting each other at about right angles. In addition to these a third series not infrequently appears, following a somewhat horizontal direction. When this latter set of cross-joints is well-developed, the rock assumes a kind of rudely bedded aspect (see Plates XXIX and XXX). Lavas and sills are usually intersected by vertical joints (Plate XXVIII), which in some cases are so symmetrically arranged that the rock acquires a prismatic columnar structure, as in the basalts of Fingall's Cave, the Giant's Causeway, and other places (see Plate XXXI).

For our purpose it is needless to go into further detail, nor is it necessary to discuss the origin of the structures described save in a very general way. That the joints of igneous rocks are due to consolidation from a state of fusion, there can be little doubt. The rocks have contracted as they cooled, and the joints, therefore, may shortly be defined as fissures of retreat. The joints of aqueous rocks may also in some cases be the result of contraction, for sediments must contract to some extent when they dry. But the desiccation of moist or water-logged sediments will not account for the regular systems of joints by which aqueous strata everywhere are traversed. All the appearances these present are

PLATE XXIX.

TABULAR JOINTS IN GRANITE, SUMMIT OF GOATFELL, ARRAN.
Photo, H.M. Geological Survey.

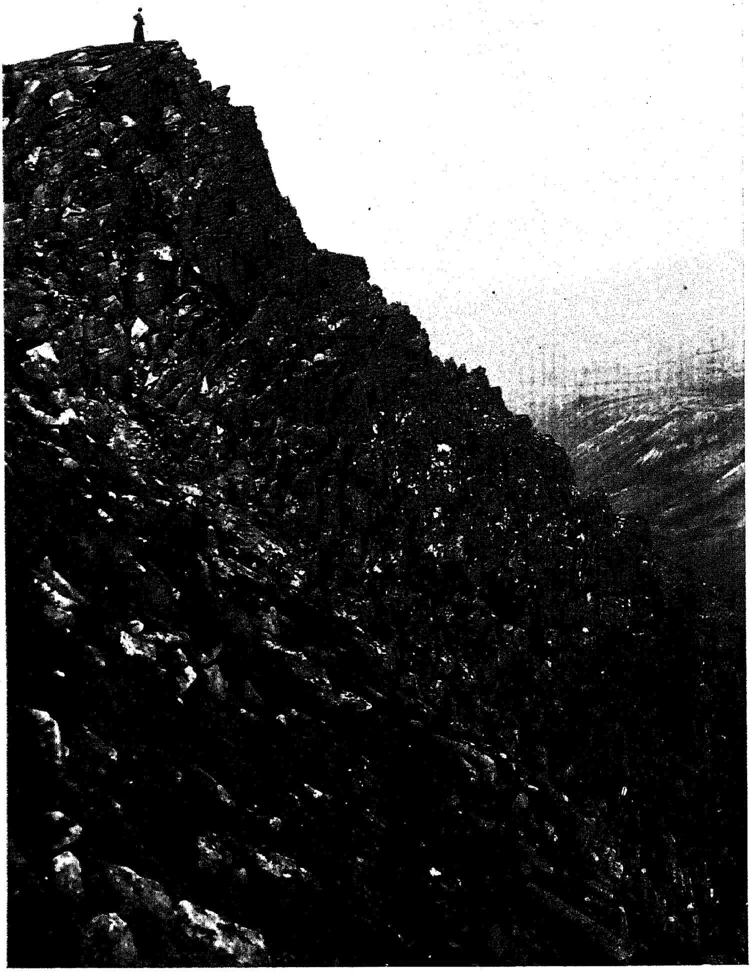
[*To face page* 147.

suggestive of powerful mechanical stress and strain. The strata have been cut through as smoothly as if they had been severed by a knife, and this is true not only of homogeneous rocks, such as limestone and freestone, but of heterogeneous aggregates like breccia and conglomerate. Had such joints been the result of contraction only, it is obvious that the stones of a conglomerate would simply have been pulled out of the rock on one side of a fissure, and left projecting from the surface of the other. Instead of this we find that the joint-planes pass without interruption through stones and matrix alike, even although the stones may consist of much harder and tougher material than the matrix in which they are embedded. When we realise that strata throughout vast regions have seldom retained their original horizontal position, but, owing to crustal movements have been folded and tilted at all angles, we can have little doubt that such movements must have resulted in the wholesale cracking and fissuring of the rocks. Tilting, however, has not been the only cause of jointing, for we find that even horizontal strata are usually jointed. Nevertheless such strata must at some time have been affected by crustal movement, for there is probably no part of the earth's surface which has not been subject to earthquake action. We may well believe, therefore, that strata, traversed by the waves or undulations caused by earthquake shocks, must have experienced strain and tension to which, owing to their slight elasticity, they would necessarily yield by cracking across.

If the jointed structure of sedimentary strata be due to crustal movement, there can be little doubt that the jointing of crystalline schists has had a similar origin. It is quite possible, of course, that in the case of some of these rocks other causes may have contributed to the production of a jointed structure. The well-defined division-planes of certain massive gneisses, for instance, may have been the result of contraction on cooling. But as schistose rocks have usually been subject to much compression, as shown by their folded and frequently crumpled and puckered structures, we may feel assured that their joint-planes must in the main be due, like those of sedimentary strata, to crustal movement.

Before leaving the subject of jointing, reference may be made just in a word to the fact that in places where rocks have experienced much crustal compression, local or general as the case may have been, they not infrequently show a rudely flaggy or even finely fissile structure, the superinduced division-planes being perpendicular to the direction of compression. Slaty cleavage described in Chapter IV is an example of general compression affecting a wide area. But again and again in regions of disturbance we come upon local areas and zones of very much crushed rocks of all kinds. These rocks are often brecciated, and tend to break up into a rubble of angular fragments; but not infrequently they are divided and subdivided by numerous approximately parallel fissures, so that they have sometimes acquired a rudely fissile or flaggy structure.

PLATE XXX.



SGÛRR GHASITHE, GLEN EUNACH, CAIRNGORM.
[Granite traversed by Vertical and Cross Joints.]
Photo, Dr Carnegie Dickson

CHAPTER VIII

ORIGINAL OR TECTONIC MOUNTAINS—*continued*

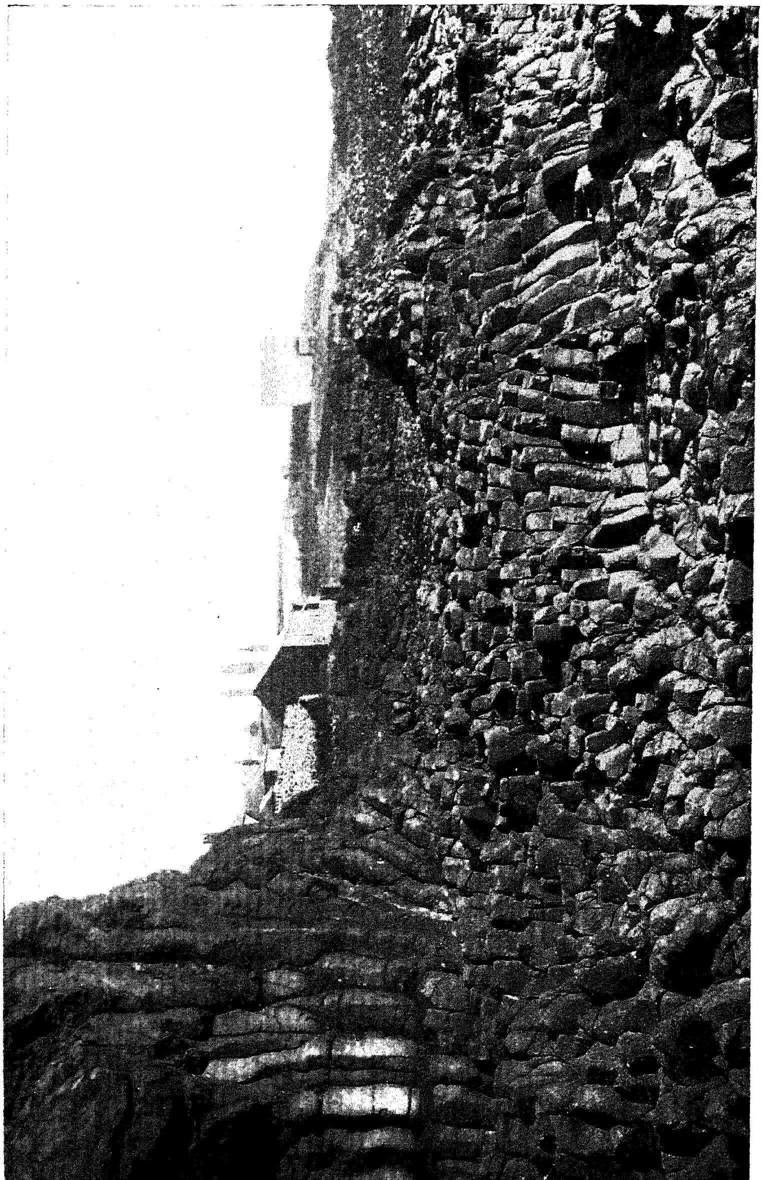
Influence of Rock-structure in determining Mountain-forms. Types developed in Horizontal Strata, as in Dolomites of Tyrol. Mountains carved out of Moderately-inclined Strata, as in the Nagelfluh of Switzerland. Erosion of more Highly-inclined Strata, as in the Limestone Alps of Säntis. Forms assumed by the Crystalline Rocks of the Alps.

HAVING briefly considered the several kinds of division-planes by which rocks are traversed, we may next pass in rapid review some of the more characteristic types of mountain-form met with in the Alps. All these, as we shall learn, are the result of denudation guided and controlled chiefly by the disposition of bedding-planes and joint-planes. But if the forms assumed by the mountains have to a large extent been determined by such rock-structures, we must also recognise that many subordinate features are due to the particular character of the rocks themselves, to their composition and state of aggregation. Any adequate treatment of these subordinate features, however, would lead us into too much detail, and is beyond the purpose of the present discussion. We must confine attention for the most part to the larger or dominant features, to those, namely, which are

determined by geological structure. Let us, therefore, consider in the first place the influence of bedding-planes in the sculpturing of mountains. All degrees of complexity of structure, as we have learned, occur amongst the stratified rocks of the Alps. But if overfolding and displacements are the most characteristic features of the architecture, it must not be supposed that these structures are equally developed in all parts of the chain. The most notable evidence of crustal deformation is encountered mainly in the northern zone; in regions further south highly inclined and much folded strata are on the whole less conspicuous. Towards the east end of the chain, indeed, there are extensive regions throughout which the younger strata are only gently flexed, occupying for the most part horizontal positions. In southern Tyrol, for example, horizontal, or very gently-inclined Mesozoic strata, resting as usual upon a pavement of ancient crystalline rocks, extend more or less continuously over hundreds of square miles. In this region lateral compression has obviously resulted in the general uplift of the whole area, without greatly disturbing the original position of the rocks.

Mountains composed of horizontal strata tend to assume pyramidal forms, the declivities of which are not infrequently corbel-stepped. Much, however, depends on the character of the constituent strata, and the thickness of individual beds. When the rocks are of similar consistency and crumble readily, the mountain slopes are not terraced but smooth, and, as a rule, descend with a rapidly diminishing

PLATE XXXI.



gradient. When, on the other hand, the constituent strata vary considerably, both as regards durability and thickness, a corbel-stepped contour is sure to develop. The outcrops of the less durable beds, readily crumbling away, form longer or shorter slopes, according as the beds are thick or thin, while the more resistant rocks, if sufficiently massive, project as great cliffs, or, if of little importance, as more or less prominent ledges. In short, the general configuration of mountains composed of horizontal strata is determined by the disposition of the bedding-planes and the joints. These are the lines of weakness along which the rocks most readily succumb; hence all mountains thus constructed have much the same aspect, although endless modifications of their outlines necessarily arise from the varying petrological character and thickness of individual strata.

In south-east Tyrol we encounter great mountain-masses of horizontal or approximately horizontal strata of Mesozoic age, the basement beds of which rest discordantly as usual upon the old crystalline schists and Palæozoic rocks. The famous Dolomite Mountains are conspicuous examples. These, as the name implies, are composed chiefly of calcareous rocks (magnesian limestones) which attain a great thickness. Two notable sheets are recognised, the lower known as the Schlern dolomite and the upper as the Dachstein dolomite. The former is a massive white rock, almost devoid of stratification; while the latter, on the other hand, is distinctly bedded throughout. Both are more or less abundantly jointed, the planes of

jointing in the Dachstein rock being as usual perpendicular to the bedding, and relatively straight or even; while those in the Schlern dolomite are similarly vertical, but as a rule somewhat more irregular or uneven. The lower dolomite has the wider range of the two sheets, and enters exclusively into the formation of many of the mountains eastward of Bozen, as the Schlern and the Rosengarten. Further on in the same direction it gradually dips at a low angle until it passes underneath the Dachstein sheet. Owing to the excessive denudation of the whole region, however, the latter occurs mostly as isolated masses or "outliers," distributed over the surface of the Schlern dolomite. The distinguishing character of the two rocks is expressed in the varying configuration and general aspect of the mountains. Owing to the absence of any bedded structure, the lower dolomite naturally shows no horizontal terracing or banding. When its joints are rather wide apart, it tends to form broad tabular heights, bounded by steep acclivities, or stout pyramidal masses, often sharply peaked, but not infrequently blunt or obtuse, both forms being well seen in the Schlern, the Sella group, and the Marmolata. With abundant and well-defined jointing, however, the mountain summits break up, as it were, into a wilderness of needle-like spires, soaring towers and steeples, and acute ragged crests, as in the Rosengarten (Plate XXXII), the Fünffingerspitze, and the Langkofl Joch (Plate XXXIII), the Latemar group, and others. In all these mountains one notes the

ROSENGARTEN MOUNTAINS, SOUTH-EAST TYROL. [Massive Dolomite with only obscure stratification ; Vertical Jointing strongly pronounced.]
Photo, Photochrom Co.

THE FÜNFFINGERSPITZE AND THE LANGKOFL JOCH, SOUTH-EAST TYROL.
[Massive Dolomite traversed by abundant Vertical Joints.]
Photo, Abraham, Keswick.

[*Between pages* 152 *and* 153.

infrequent occurrence of rectangular outlines, and the general absence of square-faced precipices. This is doubtless due partly to the unstratified character of the rock, and partly to the uneven or irregular nature of the vertical joints. Buttress, tower, and steeple may rise abruptly enough, but they are seldom defined by the straight vertical lines and perpendicular walls that are so commonly seen in the corresponding features of the Dachstein dolomite. Mountains carved out of the latter rock are thus distinguished not only by their banded or terraced aspect, but by their broad, square-faced mural precipices. The presence of such rectangular features, indeed, is as characteristic of these mountains as their absence is of the heights hewn out of the Schlern dolomite. Like the latter, the Dachstein dolomite sometimes forms desolate plateaus, with an exceedingly broken surface; but where it has been cut up into isolated masses or "outliers," these rise as massive rectangular towers or narrower peaks, defined by straight vertical joints, but everywhere showing a well-bedded structure, as in the Drei Zinnen (Plate XXXIV), the Cinque Torri (Plate XXXV), the Vajolet Thürme, and many others.

Mountains carved out of horizontal rocks, it need hardly be said, are not common in Switzerland. In most cases, indeed, the horizontality is only approximate, as in some of the snow-clad heights of the Tödi group. Tödi (11,887 feet) itself (Plate XXXVI) may serve as an example, consisting as it does of nearly horizontal but really undulating beds of limestone,

and forming an elongated and truncated pyramid with corbel-stepped acclivities. In other cases approximately horizontal and much inclined beds may be associated in one and the same mountain, as in the Bifertenstock (11,240 feet, Plate XXXVII). At the other end of the Aar massif appear several prominent heights into the formation of which strata not highly inclined, and sometimes even approximately horizontal, in like manner largely enter. As examples may be mentioned the Balmhorn (12,175 feet, Plate XXXVIII) and the Gspaltenhorn (11,295 feet), a corbel-stepped pyramid, the flanks of which are divided up into a series of subordinate pyramids and pinnacles. Mountains cut out of overthrust rocks and recumbent folds, such as the Dent le Morcles, overlooking the Rhone Valley near Martigny, and Mont Joly, at the south-west end of the Mont Blanc massif, have much the same aspect as mountains chiselled out of normal horizontal strata.

When relatively "hard" rocks are interbedded with less resistant strata, and the whole series is moderately inclined in some particular direction, the outcrops of the harder rocks tend in time to project more or less prominently. Denudation, in short, results in the structure known as "escarpment and dip-slope." Good examples of this structure are furnished by many of the Nagelfluh mountains, among the most notable being the Rossberg (Plate XXXIX) east of Lake Zug, and the Rigi between the Lake of Lucerne and Lake Zug. But when the dip of the strata is high, the more resistant rocks tend

THE DREI ZINNEN, SOUTH-EAST TYROL. [Well-bedded Dolomite traversed by Vertical Joints.]

Photo, Abraham, Keswick.

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to form narrow ridges rather than typical escarpments. Such ridges are usually steepest on the outcrop side, so that when seen in profile they appear as lop-sided pyramids. One of the most notable Alpine escarpments is that of the Churfirsten, which rises from the north bank of the Wallensee in a series of great precipices, and terminates upwards in a range of barren peaks, exceeding 7000 feet in height. This grand escarpment consists chiefly of Cretaceous limestones, etc., with a northerly dip, and is trenched and furrowed by innumerable deep gullies, hollowed out along the vertical joint-planes. The hard limestone forming the crest of the escarpment was formerly overlaid by soft shales, clays, and sandstones, now largely removed by denudation. They still occur, however, to some extent upon the dip-slope, which descends at first somewhat steeply, but afterwards more gently, into the valley of the Thur.

It holds generally true of folded strata everywhere, that an anticlinal or saddle-backed structure is less durable than a synclinal or trough-like arrangement. An anticlinal range, consisting of a succession of porous and relatively impervious strata, has no long life before it, more especially if it be flanked on either side by synclinal longitudinal valleys (see Fig. 36, p. 156). The rivers in the latter eventually deepen their courses, and in doing so they necessarily truncate the strata of the intervening anticlinal range. In this way underground water, percolating through the rocks, escapes in the form of springs at the line of junction between pervious and impervious beds. The action

of such springs, often aided by frost, results in the undermining and collapse of the pervious beds, larger and smaller fragments of which are from time to time dislodged. Not infrequently, indeed, the impervious beds, which may be clays, become so softened or lubricated by the water that they are unable to sustain the weight of the overlying rocks, which thereupon give way and slide into the valley. All the conditions are thus against the preservation of anticlinal

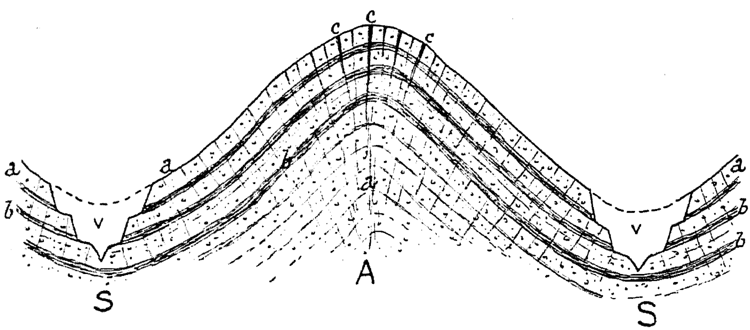


FIG. 36.—Reduction of an Anticlinal Fold.

A, Anticline; S S, Synclines; *a a*, Pervious Strata; *b b*, Impervious Strata; *c c*, Joints; v v, Synclinal Valleys.

structures. The strata hang away from the axis of the fold, and their joints tend to open out upwards, and are thus readily penetrated by water and loosened and widened by frost, so that even when the strata are homogeneous throughout, their weak arrangement nevertheless lends itself to denudation. It is otherwise with a syncline, the structure of which favours the preservation of the strata, no matter what the nature of those may be. The joints in a syncline are usually close, and as the beds incline towards and

THE CINQUE TORRI, TYROL. [Dolomite, well bedded, breaking up along Vertical Joints.]
Photo, Photochrom Co.

[*To face page* 156.

not away from the axis, they are not sapped and undermined as in an anticline, nor is there the like tendency to wholesale slipping and collapse.

One might expect, therefore, that in recently elevated folded mountains, anticlines should afford evidence of more rapid decay than synclines. The folds instead of being symmetrical may be very much the reverse; their axes may be gently or steeply inclined, but in all cases the synclinal folds must of necessity occur in the best state of preservation, for their very position serves to protect them, while the anticlinal folds curving upwards are most exposed to the assaults of the various atmospheric agents of change. There is, perhaps, no part of the Alpine area where these phenomena are better displayed than in the Limestone Alps of Säntis (Plate XL). That wild region has been studied in detail by Professor Heim, assisted by his son, Dr Arnold Heim, and Drs Jerosch and Blumer, and the results of their investigations have been set forth in an elaborately illustrated work of peculiar interest to all students of mountain-structure. The numerous admirable profile-sections accompanying the descriptive memoir show at a glance the leading features in the architecture of the Säntis Mountains. The reader may remember that these mountains form a portion of the great Helvetian rock-sheets, which during the latest phase of the crustal thrust were buckled up into folds and pressed against the Nagelfluh. The folds, as might have been expected, are asymmetrical and lean over towards the north.

Although they belong, like the folds of the Jura, to a relatively recent geological period, they have yet experienced great denudation, the anticlines naturally suffering most. But a glance at the accompanying Plate, which shows some of Heim's profile-sections on a reduced scale, will serve better than any description to make clear the character of the folds and the relative weakness of anticlinal as compared with synclinal structures.

In Plate XLI the various groups of strata represented in the sections are in descending series as follows:—

c

1. *Eocene.* —Marly shales, etc., and green sandstones. About 4000 feet.
2. *Seewerkalk.*—Impure limestones, with calcareous shales, marls, clays, etc. From 350 to 500 feet.
3. *Gault.*—Impure arenaceous limestones, shales, shelly breccias, and green sandstones. From 60 to 250 feet.

b

4. *Schrattenkalk.*—Hard limestone, with here and there intercalated beds of marl and clay. From 600 to 650 feet.

a

5. *Neocomian.*—Marls, shales, shelly breccias, and siliceous limestones. From 350 to 650 feet.
6. *Valangian.*—About 650 feet.

The Jurassic rocks which crop out in the lower part of the great escarpment of Churfirsten nowhere come to the light of day in the Säntis Mountains. Most of the folds throughout that region lean over towards north or north-west (Plate XLII). They are fairly well preserved, but the anticlines have in all cases been much reduced, the presence of the massive Schrattenkalk having failed to protect them. It is obvious, indeed, that from such anticlines as are still

PLATE XXXVI.

THE TÖDI, SEEN FROM THE CLARIDENFIRN, AAR MASSIF. [Approximately horizontal Mesozoic strata forming a truncated pyramid.]
Photo, Wehrli, Zürich.

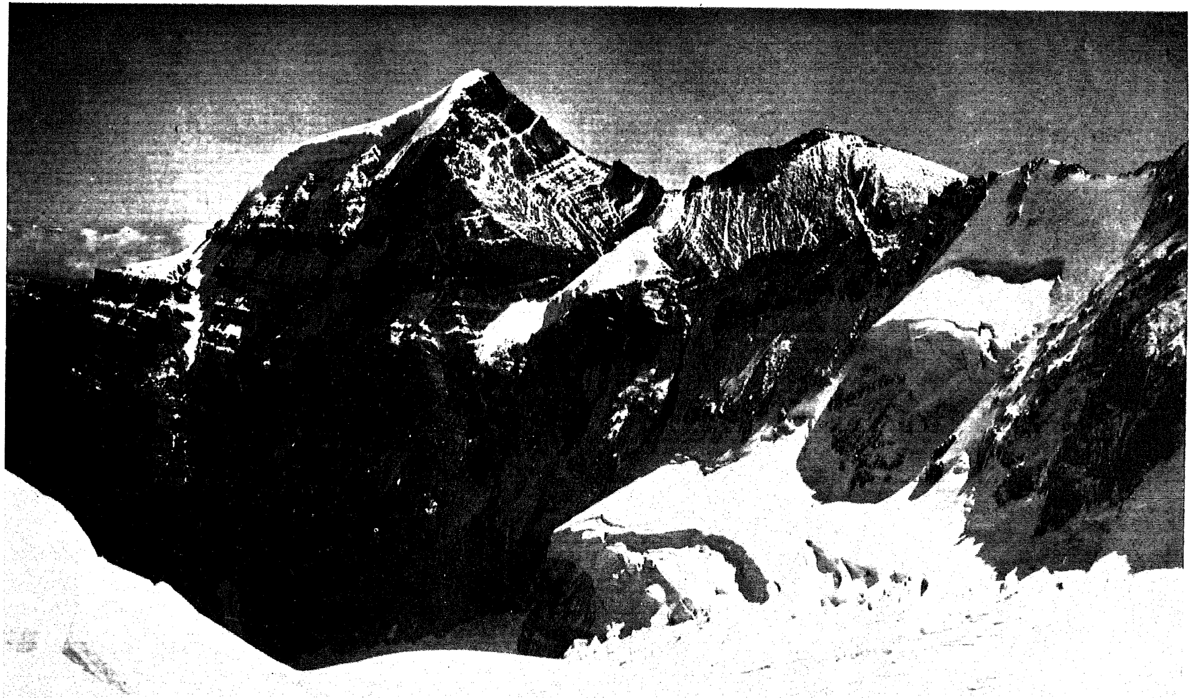
[To face page 158.

capped by that hard limestone, a covering of 400 to 800 feet of Cretaceous strata has been removed, together with an unknown thickness of overlying Eocene. A glance at Professor Heim's sections shows that the truncation of the anticlines has resulted in the development of a series of acute escarpment ridges, formed by the outcrops of the more resistant strata. The asymmetrical structure of the folds does not lend itself to the formation of synclinal mountains, a type that is only developed amongst symmetrically folded strata. Even in the Säntis region, however, approximately symmetrical synclinal folds occasionally occur, and these have been sculptured into considerable mountains, such as Neuenalpspitz (5968 feet) and Wänneli (5642 feet) near the east end of the range. Thus sooner or later geological structure asserts itself as the controlling factor in the modelling of a land-surface by denudation. Folded mountains owe their origin, indeed, to subterranean action, the crust is buckled, dislocated, and elevated, but the wrinkles and protuberances so formed offer very unequal resistance to the forces of decay. This is due, often in large measure to the character of the rocks themselves, some yielding much more readily than others; but generally it is the mode of arrangement of the various rock-masses and the character of their jointing that determines the development of mountain forms. In regions of recent elevation the construction of particular ranges is essentially weak and open to attack by the agents of erosion. Under

such conditions, therefore, rock-falls and great landslips are of frequent occurrence. In mountains of vast geological antiquity, on the other hand, wholesale collapse of the kind seldom or never takes place, for all the weak structures have long ago been demolished and only the strong ones endure.

In Chapter IV the symmetrical folds of the Swiss Jura were referred to, and it was there pointed out that notwithstanding very considerable denudation, the mountain ranges still coincided with anticlines and the valleys with synclines. It must be remembered, however, that these mountains are quite young, not older, in fact, than the Limestone Alps of Säntis. When we compare them with elevations of far greater age, constructed of strata folded in the same symmetrical manner, we note at once a remarkable contrast. In the Appalachian ranges (see Fig. 21, p. 75), for instance, the mountains coincide with synclines and the valleys with anticlines; the weak structures, in short, have been reduced more readily than the strong ones, and the primeval configuration has thus been reversed. The asymmetrical folds of the Säntis, like the symmetrical plications of the Jura, still form anticlinal mountains; but where the crowns of the saddle-backs have been removed, the highly inclined strata are already developing into a succession of sharp-crested escarpments separated by narrow depressions.

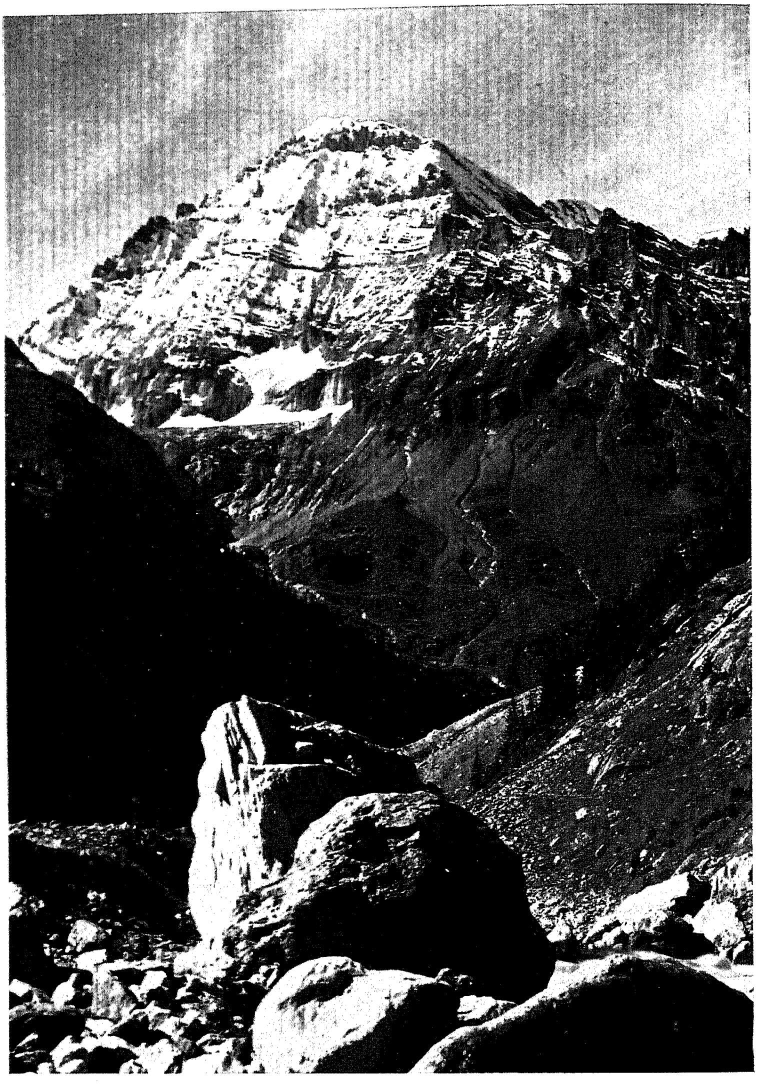
To sum up, it may be said that the forms assumed by stratified rocks under the influence of denudation vary in a more or less definite manner. Mountains



THE BIFERTENSTOCK AND PIZ FRISAL, SEEN FROM THE FIRN PLATEAU OF THE TÖDI.
[Eocene and Mesozoic strata resting upon Gneiss.]
Photo, Wehrli, Zürich.

[*To face page* 160.

PLATE XXXVIII.



THE BALMHORN, NEAR WEST END OF THE AAR MASSIF.

Photo, Wehrli, Zürich.

PLATE XXXIX.

THE ROSSBERG (R), FROM SEEBODENALP, RIGI. [Nagelfluh (Conglomerate, etc.), showing Escarpment and Dip-slope. The Mythen (see Plate XXIV.) in the background at M.]

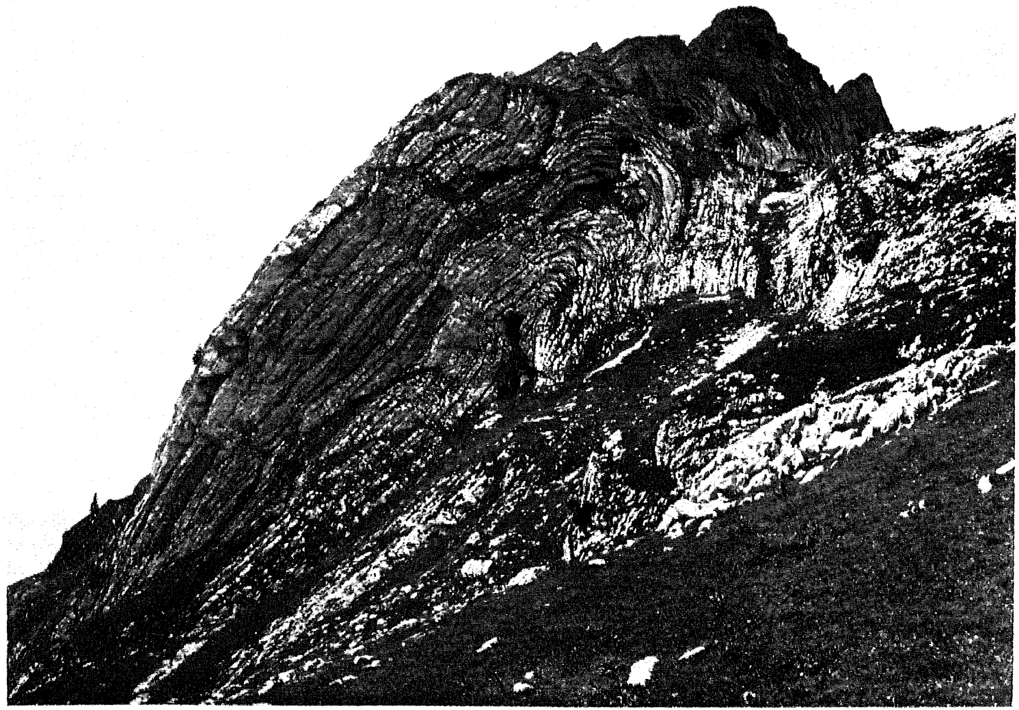
Photo, Wehrli, Zürich.

PLATE XL.

THE SÄNTIS MOUNTAINS, FROM THE HOHE KASTEN.

Photo, Wehrli, Zürich.

[*Between pages* 160 *and* 161.



ASYMMETRICAL FOLD OF THE "SCHRATTENKALK," LEANING OVER TOWARDS NORTH: SÄNTIS MOUNTAINS.

Photo, Wehrli, Zürich.

[*Between pages* 160 *and* 161.

PLATE XLIII.

THE GNEISS MOUNTAINS OF THE ETZLI THAL, FROM THE OBERALPSTOCK.

Photo, Wehrli, Zürich.

[*To face page* 161.

constructed of horizontal strata tend upon the whole to form somewhat broad-based and rather obtuse pyramids, which are often corbel-stepped. Should they be very profusely jointed, however, the pyramids may be acute and terminate in tall spire-like peaks. Again, when strata are moderately inclined they are often fashioned into obtuse, lopsided pyramids; but, with an increasing dip, should any relatively hard beds be present these are sure to project, and a succession of escarpments and longer or shorter dip-slopes will appear. When the inclination of the strata is so high as to approach verticality, the harder strata then weather into crests and ridges, varying in character with the nature of the rocks and their jointing. In elevated regions the outcrops of hard rocks such as the Schrattenkalk of the Säntis, for example, may form lines of lofty jagged pinnacles and commanding peaks. Even in the case of much contorted strata the configuration of the mountains is still chiefly influenced by the nature of the rocks and their arrangement; and as the latter is very much diversified, the forms worked out by erosion are correspondingly irregular and bizarre. Thus in one and the same mountain-group we may encounter a confused and complex medley of pyramids and more or less independent peaks, tortuous lines of escarpments, or serrated arêtes, domes, and fantastic pinnacles, in every imaginable variety.

We may now glance at the various forms assumed by the crystalline rocks of the Alps—the schists, gneisses, and granites. In the northern and southern

zones the schistose rocks occur as a rule in approximately vertical beds, while in the intervening central zone they are, over wide areas, much less steeply inclined, being in many places gently undulating and even occasionally almost horizontal. They vary considerably in composition, so that some are much more readily weathered than others. Again, while some are abundantly jointed, others are less markedly so. Usually these division-planes traverse the beds at very variable angles, and are rarely so regularly disposed as the joints of sedimentary strata. The rocks, therefore, tend to break up into irregular angular fragments of all shapes and sizes. Exceptionally, however, as we have learned, some of the gneisses are more regularly divided, and the same is the case with certain granites.

When the schists and gneisses occur in steeply-inclined and vertical beds, as throughout the great Aar massif (see Plate XLIII), they usually present a highly corrugated appearance, the more yielding strata being hollowed out along their outcrops, so as to leave the intervening harder rocks to project. All through that region, therefore, the mountains are sharply trenched and ridged in a south-west to north-east direction, the projecting ridges being everywhere abundantly notched and toothed. Owing to their variable character and the irregularity of their jointing, the rocks have naturally yielded unequally, the more resistant masses rising again and again into gigantic rugged pyramids (see Plate XLIV), and acute peaks or straggling and zigzag

serrated arêtes. The corbel-stepped acclivities and conspicuous ledges, so characteristic a feature of mountains built up of horizontal or moderately inclined strata, are nowhere visible.

Here and there the sharply corrugated outlines yielded by the schists and gneisses is interrupted by narrower and broader depressions, or relatively smooth areas, which usually mark the presence of belts of granitoid rock. When granite, however, occurs in sufficient bulk it may form broad-based and lofty pyramids, such as that of the Bietschorn (12,965 feet, Plate XLV) in the Bernese Alps. The "protogéne" granite of the Mont Blanc massif has weathered in a different fashion. The rock has been greatly crushed, and its abundant vertical fissuring has caused it to break up into sharp-crested arêtes, pinnacles, and peaks, the flanks of which are deeply scored and furrowed, and beset with countless subordinate spikes, spires, and ragged spurs and ridges, forming the famous "Chaine des Aiguilles" (see Plate XLVI).

In the central region of the Alps the gneisses assume an approximately horizontal position over considerable areas, or they may show moderate dips, being arranged in a series of broad recumbent isoclinal folds—that is to say, the folds lean over in one direction, namely, towards the north. As a result of that structure the mountain-forms differ essentially from those of the grand massifs of the northern zone. Where the beds are approximately horizontal, the highest-lying gneisses have suffered

much denudation, and are now represented by more or less isolated peaks and pyramids, such as the Matterhorn, Dent Blanche, and Weisshorn (see Plate XXV and Frontispiece). Where, on the other hand, the several series of gneisses are arranged in isoclinal folds, the crowns of the recumbent anticlines have as usual disappeared and are replaced by steep escarpments, while on the dip side the ground falls away in long rugged slopes. The general orographical features are, in short, essentially similar to those of a region composed of a variable series of sedimentary strata, having the same geological structure. It goes without saying, however, that in detail escarpment mountains carved out of bedded gneisses offer many contrasts to those hewn out of sedimentary rocks.

PLATE XLIV.

PEAKS OF THE FINSTERAARHORN AND AGASSIZHORN. [Gneissic rocks dipping at a high angle.]

Photo, Wehrli, Zürich.

[*To face page* 165.

CHAPTER IX

ORIGINAL OR TECTONIC MOUNTAINS—*continued*

Ancient Folded Mountains and their Denudation — Caledonides, Armorican and Variscan Ranges. Dislocation Mountains—Great Basin Ranges; Mountains of Moab and Palestine; Horsts of Germany; Vosges and Black Forest. Laccolith Mountains—Henry Mountains; Denuded Laccoliths and Batholiths of Britain.

In preceding chapters it has been shown that original or tectonic mountains, young and old alike, are subject to decay, and that in many cases their demolition has proceeded so far that few if any traces of the features they must at one time have possessed now remain. All stages in the destruction of volcanoes, for example, can be followed. The perfect cone is seen in a Fuji-Yama, and the final result of denudation in the abrupt stumps or cores known to geologists as "necks." Many of the latter, however, as will be pointed out more particularly in the sequel, are rather relict than original mountains. They not seldom represent volcanoes which, after having passed through a cycle of erosion, have been submerged and buried under sedimentary accumulations. Their reappearance as "necks" is due to later crustal movement and renewed denudation. But while treating of

volcanic structures it seemed more instructive to follow the history of such accumulation mountains from beginning to end, leaving to a later chapter to explain more clearly why certain necks are included in the class of original mountains, while others must be described as relict.

If it is often hard to say whether a degraded volcano be really original or relict, it is not infrequently just as difficult to decide whether a deformation folded range should be relegated to the one class or the other. Much necessarily depends upon one's point of view. The Alps, for example, when viewed in the light of their history must certainly be classified as original or tectonic. On the other hand, when we realise how excessive their denudation has been, and how the existing mountains are mere wrecks, so that their original features have been in large measure remodelled or wholly destroyed, we might well seem justified in describing them as relict or subsequent. But the relict character of mountain chains is not determined solely by the degree of denudation they have undergone. The Alps, we must realise, have not passed through a cycle of erosion. They are original mountains in the process of being lowered. And such they will continue to be until largely or wholly levelled, and, it may be, partially or completely submerged.

The probable fate of the Alps may be read in the geological history of many mountain uplifts of much greater antiquity. In Europe, for example, we have clear evidence to show that deformation

mountains of the kind have appeared at successive periods, and after prolonged denudation have been reduced for the most part to the condition of rolling plains. Thereafter submergence has ensued, and the drowned lands have been covered more or less thickly by great sheets of sedimentary accumulations. Later on the sea-floor has been uplifted to form vast elevated plains or plateaus, which in their turn have been so deeply incised by epigene action that they have assumed a mountainous character. But the mountains thus formed are relict and not original.

It has rarely happened that new ranges of folded mountains have been developed upon the site of base-levelled mountains of the same character. The process of compression seems usually to have rendered the crust more or less rigid and unyielding, so that a region which has once been buckled up and severely folded, does not yield quite in the same way if it be again subjected to tangential pressure. Should crustal movement be repeated in such a region, the tract of highly folded rocks is not as a rule refolded, but rather rises or bulges upward as a plain or plateau, with little or no additional flexing and folding.

The Alpine area, as we have learned, forms a remarkable exception to this rule. In that region the crust seems to have retained its plasticity, notwithstanding the compression it experienced in Palæozoic times, for the existing ranges were preceded in the same place by ancient mountains of uplift. The

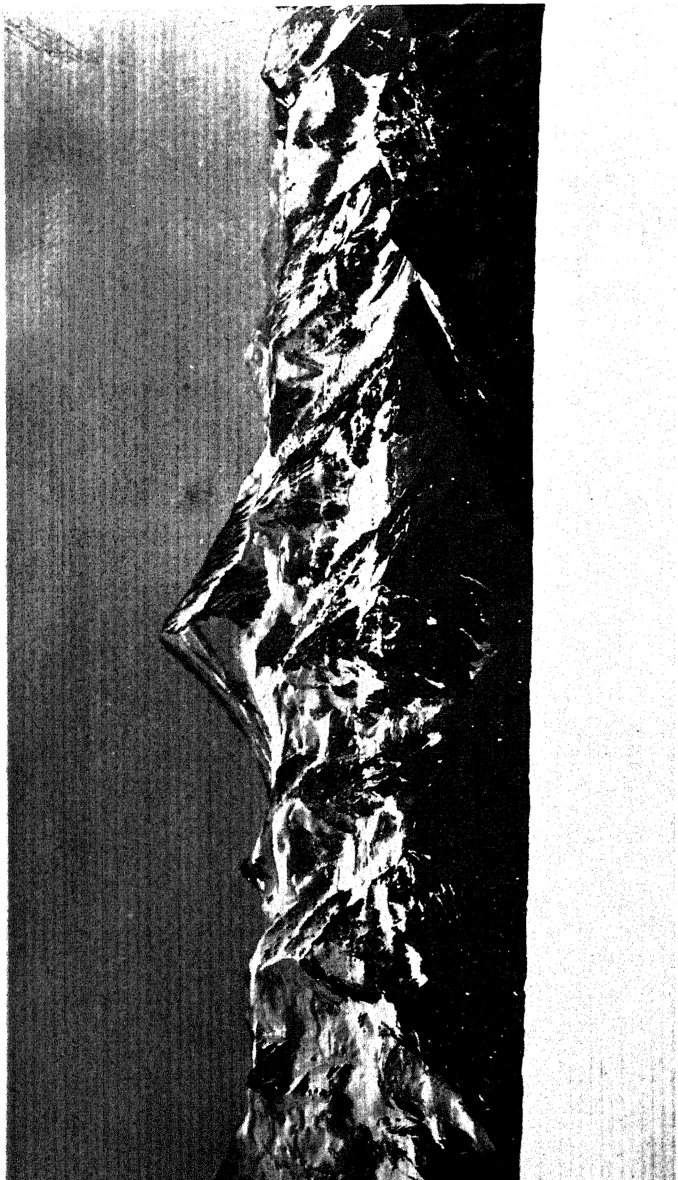
latter, sorely degraded and widely concealed under Mesozoic and Cainozoic sediments, now enter largely into the framework of the younger ranges.

As we have followed the various stages of degradation of volcanic mountains, and included in our survey certains heights that are properly speaking rather relict than original, so it may be useful to consider very shortly the history of some notable deformation mountains, the original character of which has been transformed. Although abundant remnants of these ancient mountains appear in the high grounds of Europe north of the Alps, it may be truly said of all the mountains in question that they are relict. Subjected during prolonged periods to erosion, and largely base-levelled, they owe their present elevation to subsequent crustal movement, and their configuration to epigene action alone. Not a single original mountain occurs anywhere in our Continent north of the Jura, the Alps, and the Carpathians.

In the following brief sketch of the development at successive epochs of deformation folded mountains in the regions lying north of the Alps, attention must necessarily be confined to certain salient points of the evidence. Avoiding all details of the complex geological history of the tracts in question, we shall speak only of those great crustal movements which resulted in the formation of structures essentially similar to those of the Alps and Jura.

The oldest European mountains of uplift of which we have any definite knowledge, made their appear-

PLATE XLV.

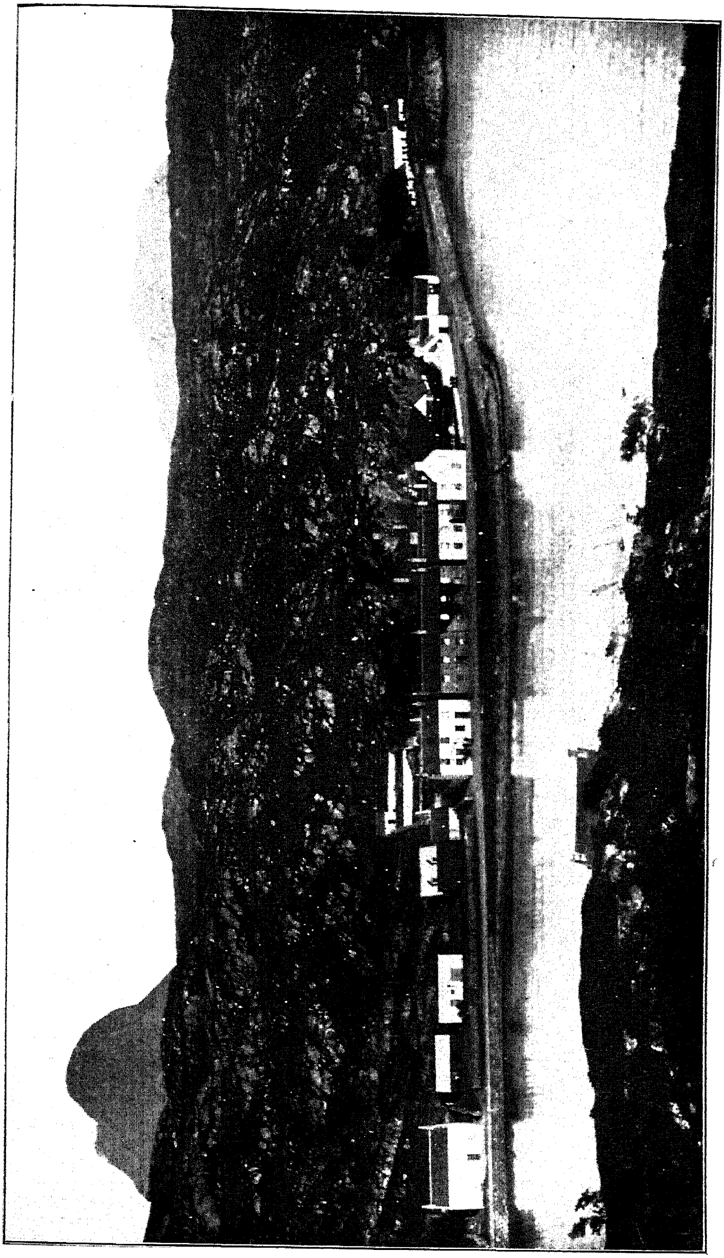


THE BIETSCHORN—A PYRAMID OF GRANITE.

Photo, Wehrli, Zürich.

AIGUILLES (CRUSHED GRANITE), OVERLOOKING THE MER DE GLACE (CHAMONIX).

Photo. Wehrli. Zürich.



PLATFORM OF ARCHÆAN GNEISS IN SUTHERLAND, with Outliers of Torridon Sandstone resting on it; Suilven to the left.

Photo, H.M. Geological Survey.

[*Between pages* 168 *and* 169.

ance in the north-west of our area towards the close of Silurian times. For long ages before their advent the distribution of land and water differed very considerably from that of the present day. Over the greater part of our continental area spread a sea of irregular but never profound depth. In point of fact, the general character of its sedimentary accumulations leads to the belief that the waters were comparatively shallow, perhaps seldom exceeding a few hundred feet in depth. And yet the Cambrian and Silurian strata that gathered over that old sea-floor reach in some places (as in the British area) a thickness of more than 20,000 feet. From this it may be inferred that the dominant crustal movement during Cambro-Silurian times was one of subsidence, for only under those conditions could such a great thickness of relatively shallow-water deposits have been accumulated. The dominant movement, however, was at times interrupted, sometimes by periods of repose, sometimes by movements in the opposite direction, when portions of the sea-floor appeared as islands. Now and again also volcanic action broke out, and lavas and tuffs thus became interbedded with the marine deposits. But beyond protracted regional movements and occasional volcanic disturbances, the crust during Cambro-Silurian times was not subjected to any extreme deformation.

The most important land of those days appeared in the far north, and extended from our north-west Highlands and northern Scandinavia for an unknown distance into regions now drowned in the Arctic

Ocean. The land in question was composed fundamentally of certain very old gneissose rocks, etc., known to geologists as the "Archæan," and we may speak of it, therefore, as the Archæan land. But over considerable areas those gneisses were concealed under thick sheets of red sandstone, etc., the "Torridonian" of geologists (see Plates XLVII, LXXI).

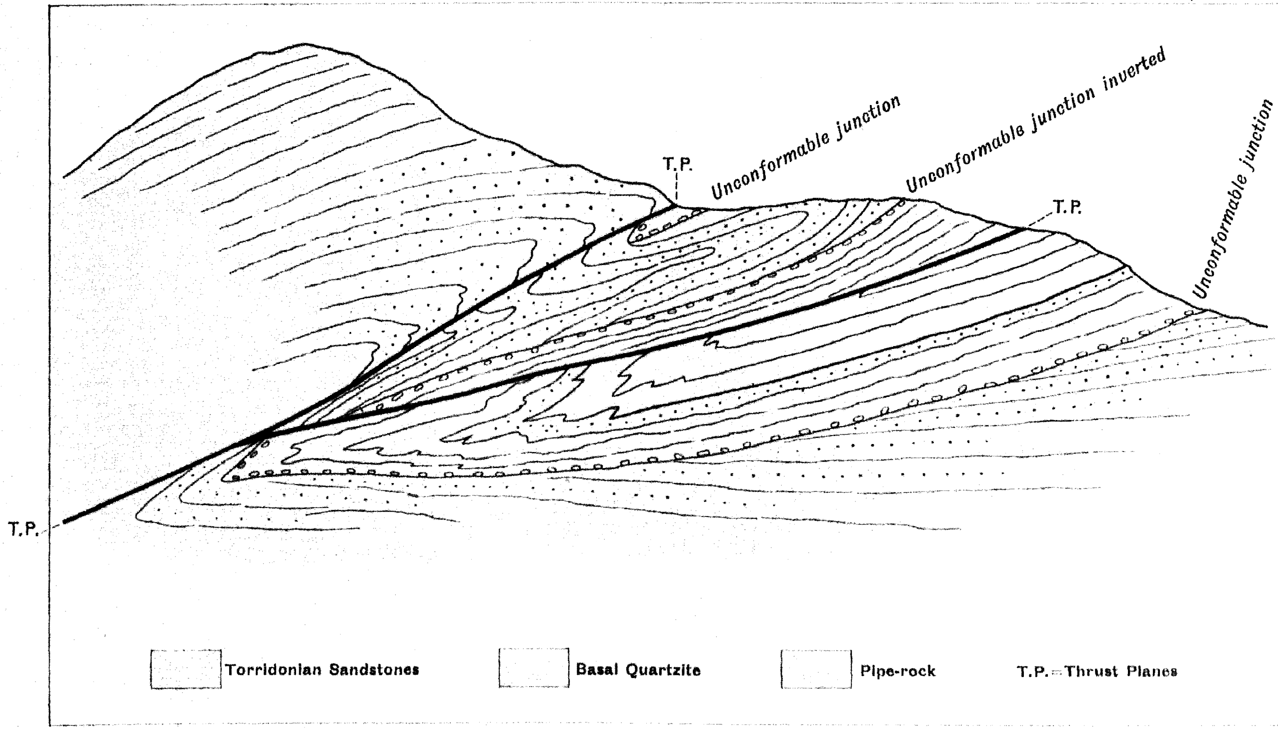
Up to the close of the Silurian period the dominant crustal movement, as already mentioned, had been one of gradual subsidence, but before the beginning of the next succeeding period—the Devonian—tangential compression of the crust supervened, and the accumulations of the Cambro-Silurian seas were buckled up and strongly folded over large tracts in north-west Europe. A great series of ranges, termed collectively by Professor Suess the "Caledonian Mountains," then replaced the seas which had previously overflowed the British area and north-west Scandinavia. The crustal movement in our region was directed towards west-north-west; in Scandinavia, on the other hand, towards east-south-east. Throughout both areas, therefore, the axes of the folds have the same trend, the average direction being from south-west to north-east. These folds are well seen in north Wales, the Lake Country, the Irish mountains (except those in the extreme south of the island), the Southern Uplands, and the Highlands of Scotland. The crustal deformation becomes more and more strongly marked as the folds are traversed from south-east to north-

NORTH FACE OF SGÙRR RUADH, ACHNASHELLACH FOREST, ROSS-SHIRE. White lines show edges of Thrust-planes.

Photo, H.M. Geological Survey.

[*To face* PLATE XLIX.

SECTION ACROSS SGURR RUADH. SHOWING INVERSIONS AND THRUST-PLANES (*B. N. Peach*)



To face Plate XLVIII.

west. In Wales, north-west England, and southern Scotland the strata are more or less steeply inclined, the folds being sometimes symmetrical, at other times leaning over to one side or the other, but seldom actually becoming recumbent, while overthrusts when they do occur are not of much importance. In the Highlands, however, the folding is more complex, the rocks being frequently highly corrugated and contorted, while overturning and horizontal displacements become more and more conspicuous as we enter the maritime tracts of Ross and Sutherland. Throughout that region the folds have been generally pushed over on their sides, and innumerable thrust-planes of all dimensions are everywhere conspicuous. The latter, indeed, are the most characteristic structural features of the north-west Highlands. In a word, the most extreme deformation occurs along the north-west marginal area of the disturbed region.

It is not improbable that all this tumultuous disturbance may have been due to the proximity of the Archæan land. The crust throughout that region had in earlier ages experienced great deformation, and become correspondingly stiffened and rigid, and tended therefore to withstand renewed tangential compression. But the movement of pre-Devonian times was too extreme to be successfully resisted. The old gneissose rocks were compelled to yield to pressure, partly by folding but chiefly by dislocation and displacement along a multiform series of planes, slice after slice, with their coverings

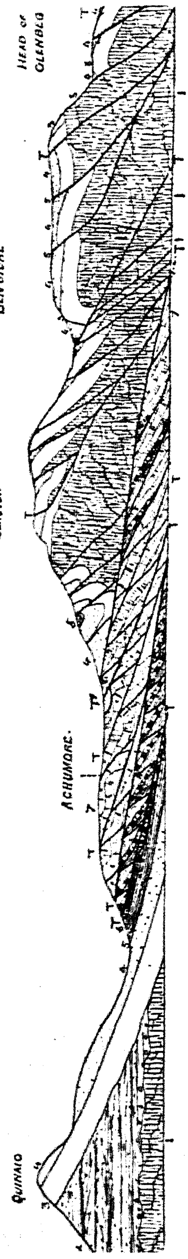


FIG. 37.—Section from Quinaig to Head of Glenbeg (*Geol. Survey*).
1, Lewisian Gneiss; 2, Torridon Sandstones (Pre-Cambrian); 3 to 7 = Cambrian; T T, Thrust-planes.

of Torridon sandstones and Palæozoic strata being forced off, and, one after another, driven upwards upon the borders of the Archæan land.

The accompanying section (Fig. 37) may suffice to show the general structures characteristic of the north-west Highlands. The reader will note that all the thrust-planes are inclined in one and the same direction, the major or most extensive thrusts (as T′ T′) being inclined at the lowest angles to the horizon. Plates XLVIII and XLIX exhibit in greater detail the phenomena of a thrust-plane. Plate XLVIII is a view of a mountain in Ross-shire, in which the following series of rocks crop out: Torridon sandstones, Basal quartzite, and Pipe rock, the two latter being of Cambrian age and resting unconformably upon the pre-Cambrian Torridon beds. The interrupted white lines are the outcrops of thrust-planes. Plate XLIX is a section taken obliquely across the

PLATE L.

MEALL A GHUBHAIS, BEN EAY, ROSS-SHIRE. A mountain consisting mainly of more ancient rocks which have been pushed from left to right over the Cambrian formations along the Reversed Fault, indicated by the feature between the two arrows.

Photo, H.M. Geological Survey.

mountain to show the general structure. From the base of the mountain up to the first thrust-plane the strata occur in their true order: thereafter it will be seen they are inverted and have been driven upward from left to right. The two thrust-planes which traverse the hill-face are branches of one and the same overthrust, as is shown in the section. Another good example of a thrust-plane is seen in Plate L, where the outcrop of the plane forms a well-marked line traversing the mountains from left to right.

Some of the major thrust-planes of the region in question are on a very considerable scale, involving as they do the translation of great sheets of rock, over a thousand feet in thickness, for distances of ten miles or more. But notable as these rock-movements are, they cannot compare in extent to the similar translations which have been recognised in Scandinavia, where in one particular case a massive sheet, many thousand feet thick, is believed by some geologists to have been driven from west to east, for a distance apparently of eighty miles or thereabout.

Such then, in a few words, are the general phenomena characteristic of the "Caledonides," the first great chain of folded mountains to appear in Europe. The chain must have extended continuously from north-east to south-west for a distance of not less than 1500 miles, with a variable width probably not exceeding 150 to 400 miles. Since the time of its formation many notable geological changes have taken place, and the old uplifted region has been pro-

foundly affected. It has been traversed, for instance, by numerous powerful vertical dislocations, some of which have the same trend as the ancient chain, while others cut across its axes of elevation at various angles. Regional crustal movements have likewise influenced the area, during which it has been first extensively depressed and widely buried under the vast sedimentary accumulations of later periods, and, subsequently re-elevated, has been largely relieved of its load by prolonged erosion and denudation. In a word, the pre-Devonian ranges have been wholly remodelled and replaced by plains and plateaus of erosion, and by more or less conspicuous relict or subsequent mountains, to the history of which attention will be directed in the sequel.

The formation of the Caledonides was thus succeeded by a protracted period of comparative repose. Crustal movements, as we have indicated, did indeed continue to take place, but these were regional rather than axial. During the subsequent Devonian and Carboniferous, just as during the preceding Cambrian and Silurian periods, the dominant movement of the crust was one of subsidence. But this was frequently interrupted by movements in the opposite direction, accompanied by some flexing and gentle folding, and by vertical dislocations of less or greater extent. Volcanic action was also strongly developed at several stages. Nevertheless no great axial uplifts, no excessive tangential compression affected the great area of pre-Devonian disturbance.

It was not until about the close of the Carbon-

iferous period or in pre-Permian times that the next epoch of mountain-making supervened. The new movement then inaugurated was directed, as the former had been, from south to north, and affected a most extensive area, stretching one may say from the Mediterranean depression as far north as the south of England. The northern limits of this highly flexed and folded tract are roughly indicated by a line drawn through the south of Ireland, south Wales, the south of England, across the Strait of Dover into Belgium, thence eastward into Germany, and finally curving south to Moravia, where it disappears under the younger uplift of the Carpathians. Throughout the whole of that widespread tract all strata of pre-Permian age are more or less strongly folded; but, just as in the case of the Caledonides, the most pronounced overthrusting took place along the northern margin of the area. Thus we see in the coalfields of Belgium highly corrugated and reduplicated folds and overfolds, and great thrust-planes, along which enormous sheets of Devonian strata and overlying Carboniferous beds have been driven. In short, we may say that everywhere along the northern borders of the disturbed region Devonian or Carboniferous strata, or both, have been overthrust upon the denuded surface of the ancient Caledonian folds.

To these pre-Permian mountains of uplift various names have been given by Professor Suess. Thus the ranges that came into existence in France he terms the "Armorican mountains," while those which

extended into middle Europe are called the "Variscan mountains." To this epoch of vigorous tangential compression succeeded, as usual, a long-continued period of comparative crustal repose. For untold ages the region was exposed to erosion, and suffered extreme denudation, so that before the dawn of the Mesozoic era the pre-Permian mountains[1] had been greatly subdued, and in many places replaced by rolling plains or low grounds. Thereafter followed a movement of subsidence when the sea overflowed the major portion of the denuded lands, the submergence extending north from the Mediterranean into middle Europe, and even involving wide regions of the ancient Caledonian tract of the British area. That wide regional movement of depression was of unequal importance, some portions of the pre-Permian land being more deeply submerged than others. Like the similar movements of earlier ages, it also was interrupted by longer or shorter periods of repose, and occasionally by more or less local or even wider-spread movements of regional uplift. It is to this particular stage in the evolution of the European Continent that the entombment of the older or fundamental rocks of the Alpine area, under their covering of Mesozoic sediments, must be assigned.

Thereafter in early Cainozoic times commenced the last great epoch of mountain-making in Europe,

[1] For these mountains it is convenient to have some collective name, such as the "Hercynian chain," suggested by the late M. Bertrand, and we may be allowed to refer to the whole region involved in the crustal compression of pre-Permian times as the Hercynian land.

which resulted in the uplift of the Pyrenees, the Alps, the Jura, and the Carpathians. In all these mountains, overfolding and overthrusts are conspicuous, especially along the northern borders of the several chains, the folded and dislocated rocks being frequently pushed over and thrust forward upon the Hercynian land, or upon tracts which had hitherto escaped severe tangential compression.

Dislocation Mountains

There now remain to be passed in review only two types of mountains that owe their origin more or less directly to deformation of the earth's crust, namely, *dislocation mountains* and *laccolith mountains*. Neither equals in importance the type we have last been discussing. Dislocation mountains now and again, indeed, constitute ranges and chains, but none of these can vie in magnitude with such elevations as the Alps, the Himalayas, or the Andes. Laccolith mountains are even less notable in their dimensions, and occur usually as isolated heights or groups of heights, and very seldom as extended ranges.

Dislocation mountains owe their existence to the fracturing of the crust—to the unequal subsidence of the ground along lines of vertical displacement. They are therefore bounded partially or completely by normal downthrow dislocations: they represent, in short, segments of the crust which have maintained their relative position, while the neighbouring tracts have broken away from them and subsided. The

most notable examples we can cite are the long parallel ranges of the Great Basin of North America —that remarkable plateau which, surrounded on all sides by lofty mountains, extends north and south for nearly 800 miles, and stretches from west to east between the Sierra Nevada and the Wahsatch Mountains for some 500 miles (see Fig. 38). This plateau is traversed throughout its length by numerous approximately parallel ranges, which sometimes anastomose or pursue irregular directions. The long parallel ranges, rising for 3000 feet to 5000 feet above their bases, are bounded by normal downthrow faults, which seem to have come into existence at the end of Cainozoic times, so that the scars or scarps formed by the dislocations are tolerably fresh. The ranges might be tersely described as long rectangular blocks, which have been tilted sometimes to the west, sometimes to the east, the general structure being diagrammatically expressed in the accompanying illustration (Fig. 39, p. 179). According to the late Professor Le Conte the Basin ranges would appear to represent the disjointed segments of a great geanticline.

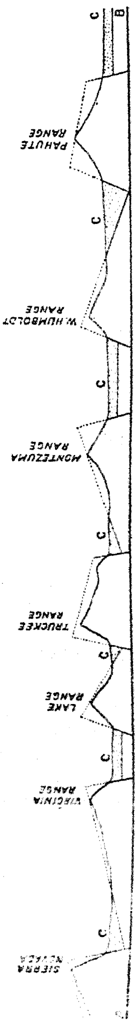


FIG. 38.—Parallel Ranges of the Great Basin, North America. (After Russell Hinman.)
A to B = 120 miles; C C C, Superficial Deposits.

At the close of the Cainozoic era the entire area now occupied by the Basin, including the Sierra Nevada on the one side and the Wahsatch on the other, was compressed from west to east or east to west, and uplifted as one broad and long extended arch or geanticline. Yielding to the tension or stretching caused by the upward bulge, the crust split or cracked, the dominant lines of fracture coinciding in direction with the axis of uplift. When the movement of elevation ceased the shattered arch slowly collapsed, its several segments settling down unequally in various directions to form the Basin Ranges, leaving

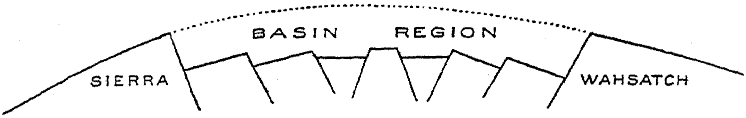


FIG. 39.—Diagrammatic Section to illustrate the General Structure of the Great Basin Ranges. (After Le Conte.)

the abutments of the geanticline, represented by the Sierra Nevada and Wahsatch Mountains, facing each other across the intervening depressed area of the Basin. Le Conte remarks that the process described must not be imagined as having been rapid or catastrophic, but gradual and protracted, "the lifting, the breaking down, and the readjustment all going on at the same time."

No dislocation mountains comparable in extent to those of the Great Basin are known elsewhere, although fault-scarp heights of recent formation are not of infrequent occurrence. All these invariably overlook more or less abrupt depressions. Of such a character are the mountains of Moab and Palestine,

which dominate the notable depression of the Jordan and the Dead Sea. The mountains in question are obviously fault-scarps, between which a long rectangular crust block has dropped down. The same type of mountain is well represented in our own Continent by numerous "Horste," as they are termed by German geologists. A horst or block mountain is rarely surrounded completely by faults. Usually heights of the kind rise, as it were, between two

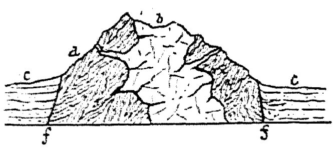


FIG. 40.—Horst or Block Mountain.
a, Palæozoic Rocks; *b*, Igneous Rock; *c c*, Mesozoic Strata; *ff*, Faults.

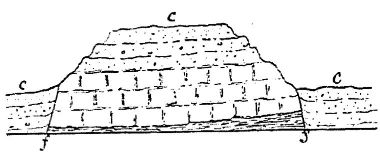


FIG. 41.—Horst or Block Mountain.
c c, Mesozoic Strata; *ff*, Faults.

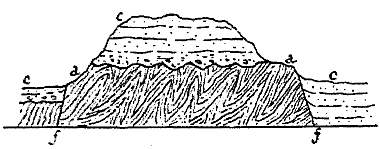


FIG. 42.—Horst or Block Mountain.
a a, Palæozoic Strata; *c c*, Mesozoic Strata; *ff*, Faults.

main more or less parallel dislocations, while not a few are bounded thus on one side only. Some of the German horsts consist entirely or very largely of highly folded and often metamorphosed Palæozoic strata, together it may be with intrusive igneous rocks (see Fig. 40), while others are composed chiefly of horizontal or gently-inclined strata of Permian, Mesozoic, and Cainozoic age (Fig 41). In many cases, however, both sets of rocks are present,

the horizontal or slightly disturbed series of younger strata resting unconformably or discordantly upon the much folded Palæozoic rocks (Fig. 42).

The significance of these structures may be briefly indicated. It will be remembered that after the uplift of the extensive continental tract, of which the Armorican and Variscan ranges were conspicuous parts, a long period of repose supervened. Exposed for unnumbered ages to denudation, that old Hercynian land became profoundly modified, its mountains being reduced in many places to the condition of rolling plains and lowlands. The ranges in question, however, were not everywhere wholly subdued, but continued to be represented by occasional isolated heights, or more continuous tracts of high ground. Long before the close of the Permian period the degradation of the land had made great progress, for we find the deposits of the inland seas and salt-lakes of that and the subsequent Triassic period resting discordantly on the truncated folds of the older Palæozoic strata. To such an extent had the Hercynian mountain-land been worn down ere the dawn of Jurassic times, that when at last it sank in the seas of that period only a few unsubdued heights or "torso mountains" remained as islets to represent it. Athwart the drowned tracts of middle Europe, just as over the submerged Alpine area, sediments of various kinds thereafter continued to accumulate throughout the later Mesozoic and Cainozoic ages, so that the Hercynian land-surface eventually became, over wide areas,

buried under great depths of sandstones, shales, and limestones.

By and by re-elevation followed, and far-stretching plains and tablelands replaced the sea throughout middle Europe. This wide regional uplift was in all probability contemporaneous with the great axial uplift of the Alps, Jura, etc., but no such folded mountains were developed anywhere throughout the new-born lands of middle Europe. Minor crustal flexures and undulations appeared, and doubtless influenced the surface, but by far the most notable features were produced by numerous vertical fractures and displacements that traversed the region in different directions. Between approximately parallel faults of this kind, wider and narrower segments of the crust slowly subsided, while many similar segments of larger or smaller extent retained their position; the ground on one or both sides sinking to a lower level. Other fault-bound tracts, on the other hand, appear to have been pressed upwards. The land-surface, therefore, was far from being plain-like throughout. Here and there rose abrupt "torsos," some of which had previously existed as islands in the vanished Mesozoic seas, while not a few were horsts, consisting of Mesozoic strata above and more ancient rocks below.

Downthrow and upthrow movements of the crust along lines of dislocation, probably in most cases proceed as gradually as the tangential thrusts to which folded mountains owe their origin. We may well believe, therefore, that the features produced by the warping and fracturing of the crust throughout

middle and western Europe must have been contemporaneously modified by denudation. The trend or course of an active river would seem to be as little influenced by faulting as by folding; a drainage-system once started tends to persist. Hence rivers are often found traversing fault-escarpments which could not possibly have existed before those rivers commenced their work of erosion, otherwise the course of the latter must have been deflected. That no such deflection has taken place is clear proof that an active river reduces any inequalities of level due to faulting as fast as these appear. Away from lines of constant water-flow the rate of denudation is not nearly so rapid, and rarely, or perhaps never, keeps pace with crustal movement. Outside of river-valleys, therefore, vertical dislocations often develop strongly marked surface-features; great wall-like scarps sometimes continuing for miles across country between one valley and another.

But while this holds true, especially in the case of recently dislocated areas, it must not be supposed that fault-scarps and other features caused by crustal deformation are secure from obliteration save in river-valleys. No part of a land-surface remains for any time uninfluenced by epigene action. The continuous operation of wind and rain, of frost and other agents, has sufficed to bring about great changes, immense thicknesses of rock having been gradually disintegrated and removed from the whole surface of a land long exposed to such action. It is quite in accordance with the results produced by denudation

in many other regions to find that the fault-scarps and horsts of middle Europe, which date their origin to the last general uplift, are now in a sorely reduced condition.

The phenomena are well illustrated by the Vosges and the Black Forest. These mountains show escarpments that face each other across the broad valley of the Rhine. Before the appearance of any Rhenish depression the Vosges had been continuous with the Black Forest, the two forming together a broad swelling or anticline, consisting of a core of ancient crystalline rocks overlaid by a great succession of Mesozoic strata. Eventually the anticline was traversed from south to north by two powerful parallel dislocations (accompanied by several minor faults) between which the crown of the arch gradually dropped down to form the Rhenish depression. It is not quite clear whether the anticlinal swelling had been in existence before the faulting occurred. Not improbably they were in a manner contemporaneous, the tension in the rising arch producing the rectilineal rents, along which subsidence afterwards took place. Whatever the case may have been, there can be little or no doubt that both upward and downward movements must be assigned to the same period of crustal deformation. The general structure of the mountains is shown in the accompanying sketch-section (Fig. 43). The abruptly truncated beds on the dip-slopes of the mountains have obviously been cut back by long-continued erosion, and originally extended continuously over the whole

area. That they formerly did so is demonstrated by the fact that the strata which occupied the crown of the anticline now occur in the Rhenish depression, wedged between the faults that brought them down.

The Vosges and the Black Forest, therefore, are true dislocation mountains, and might well be cited as types of fault-scarp mountains. If the features due to crustal action are in their case not so fresh as in that of the more recently formed ranges of the Great Basin, this is no more than might have been

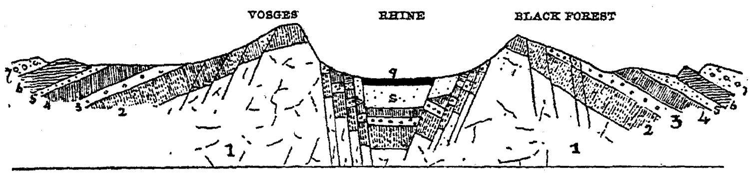


FIG. 43.—Section across the Vosges and Black Forest. (After A. Penck.)
1, Granite, etc.; 2-7, Mesozoic Strata; 8-9, Cainozoic and Later Strata.

expected. Nor, on the other hand, is it surprising that the horsts and fault-scarps of middle Europe are in a very much better state of preservation than those of our own islands, most of which date back to far more remote periods. So great has been the denudation of north-west Europe since the uplifts of pre-Devonian, and even of pre-Permian times, that the features due to fracture and displacement are seldom conspicuous. They have been so reduced and modified that frequently the actual presence of a fault can only be detected by a geologist after careful investigation of the ground. Nevertheless, even in

such regions, it is not uncommon to find low-lying tracts abutting abruptly against elevated areas, the junction between the two corresponding more or less closely with a line of dislocation. A case in point is that of the Scottish Grampians, which rise somewhat suddenly above Strathmore. The mountains consist of relatively hard rocks, the low grounds of much less durable materials, and the one series is separated from the other by a great fault or series of faults. But many thousand feet of rock have been gradually removed from both Highlands and Lowlands since these movements occurred, and it is obvious, therefore, that the present surface features must be due solely to denudation. By bringing softer rocks into juxtaposition with rocks of greater durability, faulting has no doubt determined the relative positions eventually attained by high ground and low ground. But whether at its inception the faulting ever actually showed at the surface as a series of fault-scarps cannot be asserted. It may or it may not; all we can be sure of is that no trace of any such scarps now exists. The present surface-features, in short, owe their origin directly to the unequal resistance to erosion offered by the rocks on either side of the dislocation or dislocations: they are only indirectly the result of crustal deformation.

As will be set forth more fully in the sequel, the geographical distribution of the great class of relict or subsequent mountains has in like manner been determined in the first place by crustal movements of one kind or another. Nay more, the forms these

mountains assume depend upon the nature and structure of their constituent rock-masses in even a more marked degree than is the case with deformation mountains. From one point of view, therefore, tectonic and relict mountains alike owe their origin to crustal movements, directly in the case of the former, indirectly in the case of the latter.

Laccolith Mountains

This type of mountain is the result of subterranean igneous action, the crust having bulged upwards owing to the pressure from below of a concealed mass of molten rock. The latter has risen along one or more vertical fissures, pipes, or funnels, but with insufficient force to break a passage for itself to the surface. Unable, therefore, to establish a volcano, it has insinuated itself at a less or greater depth along some plane of weakness in the crust, such as a plane of bedding, and has thus lifted the superjacent rock-masses and produced a local swelling of the ground. This type of mountain was first described by Mr Gilbert in his account of the Henry Mountains of Utah, the intruded rock being termed by him a "laccolite" or stone cistern (see Fig. 44, p. 188). Frequently subordinate intrusions have proceeded from such a laccolith, some of which assume the form of approximately horizontal "sheets" or "sills," while others have cut across the rocks at all angles and now appear as "dykes" and "veins."

The laccoliths of the Henry Mountains occur singly or in clusters, each cluster forming a more or less prominent dome-like tumescence at the surface—a mountain in short, which may rise some 5000 feet above the plateau in which it has been developed. The geological structure leaves one in no doubt that these intrusions did actually modify the surface of the ground. Even when the rocks which formerly covered and concealed the igneous mass have been removed by denudation, we can

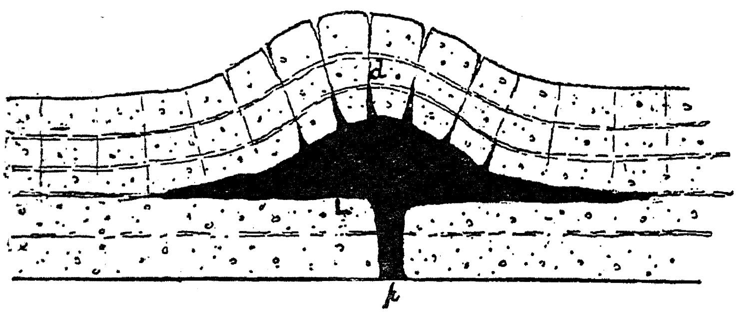


FIG. 44.—Laccolith Mountain.
L, Intrusive Igneous Rocks, sending out Dykes and Veins into Overlying Strata, *d*; *p*, Pipe or Feeder of L.

yet see that the horizontal strata of the plateau always curve upwards as they approach a laccolith. In many cases, indeed, denudation has not yet succeeded in wholly removing the superjacent strata, and the original dome-like configuration has been preserved. This is not strange when we realise the relatively recent age of the intrusions, which do not date back beyond late Tertiary or post-Tertiary times. Laccoliths of fundamentally the same character as those described by Gilbert, form groups of

mountains in Colorado, Arizona, and elsewhere in North America.

In our own country, as we have seen, evidence of former igneous action is conspicuous enough. Not only do we possess remnants of true volcanoes, but in many places masses of igneous rocks are encountered, which we have every reason to believe originally consolidated below ground, the rocks that formerly concealed them having long since been removed by denudation. Many of these rock-masses form conspicuous features, especially in lowland tracts, where they appear as prominent ridges, undulating and often broken high ground, small plateaus, or more frequently as pronounced escarpment hills. There can be little doubt that the intrusive rocks referred to are of the nature of laccoliths. The strata with which they are associated, however, are seldom horizontal, as is the case with the relatively undisturbed strata of the Henry Mountains. On the contrary they are usually inclined, and it is obvious, therefore, that the laccoliths of Britain have been flexed and folded along with the strata amongst which they were intruded. As the crowns of the anticlines have long since been demolished, our laccoliths, owing to their superior durability, now crop out boldly. They have protected the strata on which they rest, while the formerly overlying strata have been removed. It is obvious, however, that such hills owe their origin only indirectly to igneous action and crustal movement. Our sills at the time of their intrusion may have caused some tumescence at the

surface, but if any dome-like bulging ever existed, no trace of it can now be seen; all the features presently visible are the result of denudation. The hills in question, therefore, are truly subsequent.

The diagram (Fig. 45) illustrates the general structural features of a sill. Many of the Scottish examples consist of such basic rocks as dolerite and basalt, while others are formed of more acid intrusions, such as quartz-porphyry. Numerous conspicuous and well-known hills in the Lowlands owe their origin to the presence of sills, such as Traprain

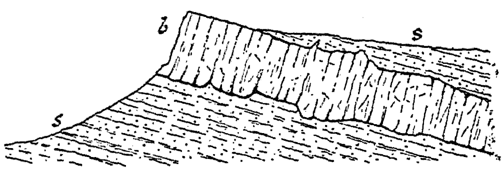


FIG. 45.—A Sill or Intrusive Sheet.
b, Sill of Basalt; *s s*, Sandstones and Shales.

Law, in Haddingtonshire (Plate LI); Salisbury Craigs, Corstorphine Hill, Dalmahoy Hill, and others in the neighbourhood of Edinburgh; and Abbey Craig, near Stirling. Drumadoon in the south-west of Arran (Plate XXVIII) is also an excellent example.

Another type of igneous intrusion well represented in our islands is that known as a *boss* or *batholith*, of which the most characteristic representatives are granites or granitoid rocks. Batholiths often constitute individual mountains or mountain groups (Fig. 46). Such igneous masses probably in most cases cooled and consolidated at greater depths in

TRAPRAIN LAW, EAST LOTHIAN. Outcrop of a Sill or Intrusive Sheet.

Photo, H.M. Geological Survey.

the crust than laccoliths. Nevertheless many have the laccolitic habit, numerous sills, dykes, and veins proceeding from them. Not a few batholiths, indeed, assume the form of enormous sheets that follow an

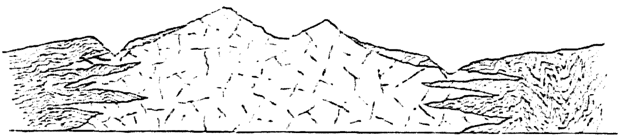


FIG. 46.—Batholith sending out Sheets into Contiguous Strata.

irregular course through the rocks amongst which they have been intruded (Fig. 47); so that batholiths and laccoliths cannot be said to be strongly differentiated. The fact that rocks of more or less deep-seated or plutonic origin now appear at the surface is of course sufficient proof that mountains composed

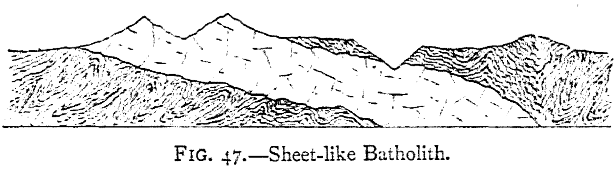


FIG. 47.—Sheet-like Batholith.

of such cannot be included in the tectonic or original class. It is quite possible that the uprise in the crust of a prodigious plutonic mass may have been marked by conspicuous swelling or bulging at the surface. But if any such deformation resulted, it must necessarily have vanished with the removal of the thick sheets of rock underneath which the concealed igneous mass cooled and consolidated. Batholiths usually form heights, for the simple reason that the constituent rock is generally more resistant than those among

which it has been intruded. Not seldom, however, the latter are the more durable, and when such is the case they constitute hills or mountains overlooking and even surrounding low plains of the plutonic rock.

Batholiths of granite are, as a rule, of great geological age, and appear usually to have consolidated at very considerable depths from the surface. Some of our Scottish granites, however, do not date back beyond Tertiary times, and would seem to have been of much less deep-seated origin: such, for instance, is the case with the young granites of Arran and Skye. Mountains composed of granite vary considerably in configuration. Some appear as abrupt dome-shaped hills, or as heavy broad-shouldered masses with a rather monotonous outline, while others show greater variety of feature, much naturally depending on the character of the rock. When this is constant, the same texture and structure prevailing everywhere, the rock tends to break up and weather somewhat equally. But with greater variability as regards texture and structure, and the nature of its constituent minerals, notable irregularities of feature are sure to result. It is more particularly, however, the character of the jointing in such cases that determines the configuration of a granite mountain. When the joints are very numerous and quite irregular in direction, the rock usually crumbles into a rubble of debris; it is less readily reduced, however, when the joints are regular and not too closely set. In one and the same batholith, therefore, we may see long scree-slopes sweeping down from the very crest of a mountain,

while in other places the screes may be interrupted by projecting and often ruinous bastions; or, instead of being curtained by screes, a mountain may be girdled by lofty precipitous cliffs, rising abruptly from the low grounds like the walls of some cyclopean masonry (see Plates XXIX and XXX).

One of the more notable Scottish granite mountains is Goatfell, in the island of Arran, of which a distant view is seen in Plate LII. Like most granites that of Goatfell is abundantly but in many places somewhat irregularly jointed. Both vertical and cross joints are well developed, the latter being especially conspicuous at the summit of the mountain (see Plate XXIX). It is needless to say that the denuding agents in their work of destruction take advantage of these several division-planes, and the rock becomes broken up into blocks of all shapes and sizes, the forms and dimensions varying with the disposition and regularity or irregularity of the jointing. Massive igneous rocks usually have a "rift" or "grain" in the direction of which they are most readily divided. And it is probable that the presence of this "grain" aids rain and frost in breaking up and shattering the blocks wedged out along the planes of jointing. The ruin caused by "weathering" is well seen in Plate LIII.

The Red Hills of Skye may be taken as good examples of the conical or dome-shaped type of granite mountains (see Plates LIV, LV). Their form strongly recalls that of the trachytic domes of

Auvergne (p. 15), so much so as to suggest that not improbably each hill or closely related group of hills may be "the result of emission from an independent funnel." It would seem, however, that most of the hills in question (and probably all) are portions of one great batholith, from which numerous sheets or sills pass outwards into the surrounding rocks. The uniform and homogeneous character of the rock has caused it to yield equally to weathering, and this is believed to have determined the regular contour and relatively smooth slopes of the hills. But while weathering may explain the flowing outlines, it does not account for the origin of the hills. Whether occurring isolated or in groups, they would seem to be not secondary but original features, doubtless greatly modified by denudation. It is not necessary, however, to suppose that each hill marks an independent eruption. The great batholith would seem to have had a very irregular upper surface. Just as it sent out lateral sills and veins, so it penetrated the overlying rocks with massive cone-like and dome-like protrusions, and it is these that are now represented by the Red Hills. This suggestion receives some confirmation from the fact that now and again the dome-shaped contour of a hill would seem to be determined directly by a rudely concentric structure of the granite, the rock being "disposed in massive sheets or beds that plunge outwards from the centre of the hill at angles of 30° to 40°." Such a sheeted structure is by no means uncommon along the marginal areas of great eruptive masses, and is not

improbably the result of pressure caused by the intrusions themselves.

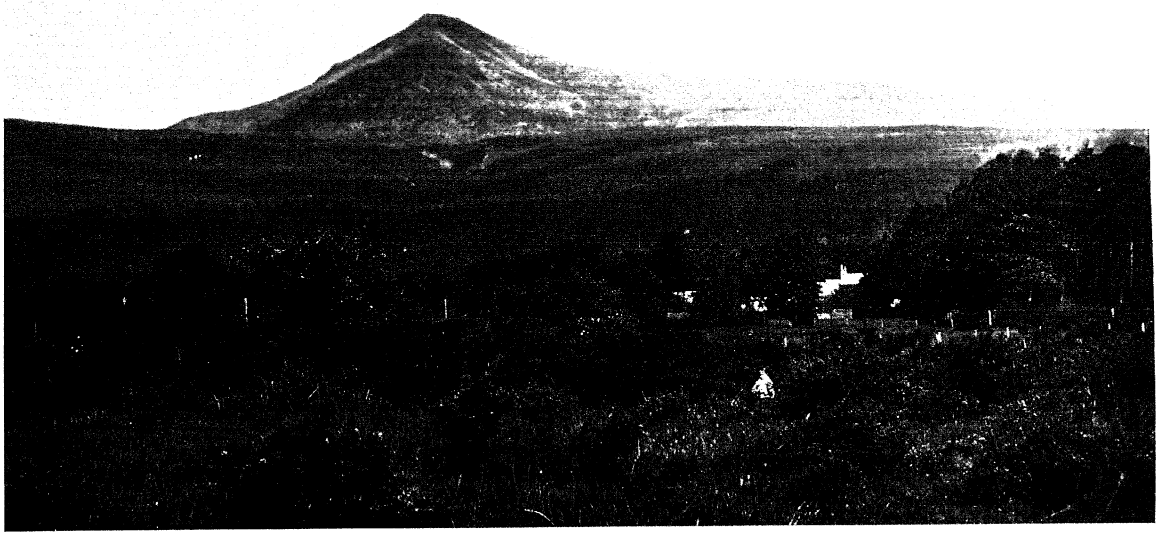
Being usually shrouded in sheets of loose rock-rubble and tumbled blocks of all sizes, the Red Hills show very little vegetation. Their general smooth-flowing contours are now and again gashed by gullies, and interrupted by projecting ribs or outstanding bastions, marked by the jointing usually characteristic of granite. Whether the bare rock comes to the surface or is concealed under long trailing screes, the hills never fail to show their characteristic colour, the tint, however, varying with the atmospheric conditions. In dull weather it is a pale yellowish grey, but in brilliant sunshine, especially in the evening and after rain, the colour deepens to orange and crimson.

Batholiths are not by any means always composed of granite. Some consist of the less acidic rock known as syenite, while others are masses of such basic rocks as diorite, dolerite, and gabbro. The Coolin Hills, for example, are carved out of a great boss of gabbro, and similar intrusions of the same rock occur in other islands of the Inner Hebrides. All these gabbro masses have much in common with the laccolith type of intrusion, numerous sills and dykes proceeding from them into the surrounding rocks. Although they are among the youngest igneous rocks of Britain, they have yet suffered severe erosion. Both in configuration and colour, the Coolins offer the strongest contrast to the Red Hills (see Plate LIV). Not only are they higher,

but altogether more precipitous, shooting upwards in numerous sharp peaks and soaring pinnacles, or abruptly notched crests and straggling rugged ridges. Their crags are harsh and rough beyond description, while the total absence of vegetation, and the dark, almost black aspect of the rock, intensify the savage desolation of the scenery. The general view (Plate LVI) gives some idea of the configuration of the mountains, while the nearer view (Plate LVII) shows how the gabbro weathers. The rock, it will be observed, is abundantly jointed, the most pronounced joints being approximately vertical. It is to the presence of these that the notched and jagged outlines of the mass are mainly due; many of the deeper clefts and gullies, however, have been hollowed out in dykes of a more readily reduced character than the rock they traverse.

It is interesting to note that the gabbro of the Coolins is an earlier intrusion than the granite of the Red Hills, the granite invading the gabbro in all directions. The junction of the two rocks is shown in Plate LVIII, where the upper and darker part of the photograph represents the gabbro and the lower paler portion the granite.

PLATE LII.



GOATFELL (GRANITE MOUNTAIN), FROM BRODICK, ARRAN.

Photo, H.M. Geological Survey.

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CHAPTER X

ORIGINAL OR TECTONIC MOUNTAINS—*continued*

Are Folded Mountains always Lines of Exceptionally Thick Strata? Hall's Gravitational or Geosynclinal Theory of the Appalachian Mountains. Dilatation or Expansion Theory of Mountain Formation. Modern Compression Theory. Folded Mountains developed in the Labile or Unstable Zone where Oceanic Basin and Continental Plateau meet.

HAVING now passed in review the more important kinds of deformation mountains, with special reference to their structure, and come to certain conclusions as to the immediate cause or causes of that structure, we have still to trace the story further back. But this, we shall find, is a much harder task. It is not difficult to read the meaning of the various geological structures that characterise deformation mountains, and we may feel justified in concluding that all such mountains owe their origin to crustal movements of one kind or another. But this does not exhaust the question of origin. We have still to consider certain views of mountain formation which have been advanced from time to time, and strongly supported by many able geologists. The apparent connection between the upheaval of mountain ranges

and volcanic action must also engage our attention; while the relation of volcanoes to fractures and dislocations of the crust calls for some notice.

Before attempting to describe the more recent developments of orogeny, we may profitably review certain ingenious theories of the origin of uplifts which until recently have been more or less favourably received. It was for long a generally accepted opinion that these mountains are invariably characterised by the extraordinary thickness of their constituent strata as compared with the much feebler development of the same rocks in the adjacent low grounds. The folded strata of the Appalachians, for instance, are supposed to attain a thickness of 30,000 feet or 40,000 feet in the chain, and to thin out westward in the Mississippi basin to 4000 feet. Again, the strata which in the Wahsatch Mountains are said to be 30,000 feet thick dwindle away eastwards to 2000 feet in the plains. In another North American range, the Laramide Mountains, the buckled up rocks, it has been stated, reach the enormous thickness of 50,000 feet. These measurements, it must be mentioned, make no claim to exactness; they are only approximations. Moreover, they were made before the extreme complexity of the geological structure of such mountains had been realised. Not only are the strata of mountain uplifts duplicated and reduplicated by mere folding, but the occurrence of more or less numerous thrust-planes with their accompanying translated rock-sheets, must necessarily increase the apparent thickness of the

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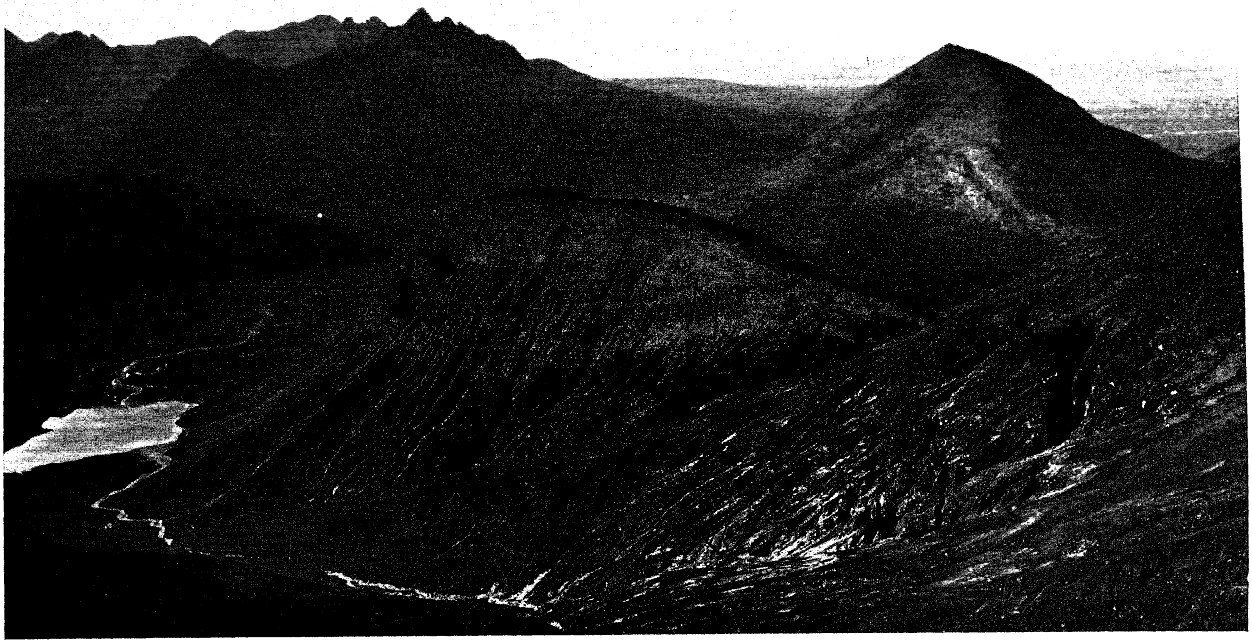
strata involved. The probabilities that the estimates referred to are excessive, therefore, can hardly be doubted. But even if considerable exaggeration be allowed for, still this cannot be so excessive as to negative the conclusion that the particular mountains mentioned occupy areas of special accumulation. It is going too far, however, to assume that all uplifts must necessarily resemble these American examples in being "lines of exceptionally thick strata." Many chains are very imperfectly known, and whether or not these indicate areas of special accumulation no one can say; while recent investigations in the Alps and other European uplifts of Tertiary age lead to the belief that the thickness of their constituent strata is not so great as was formerly supposed. It is doubtful, indeed, if in all these ranges the strata are of very exceptional thickness, as compared with the same formations occupying the adjacent low grounds. The complex folding and the piling of enormous rock-sheets one upon another, now recognised as characteristic of most folded ranges, may in some cases be sufficient to account for the apparently great thickness of the strata.

James Hall, a well-known American geologist, appears to have been the first to formulate the opinion that a deep trough or basin of deposition has in all cases preceded the process of mountain-making. In his view, therefore, the materials of which our folded mountains have been constructed were slowly accumulated in elongated depressions of the crust. The strata thus accumulated are

chiefly or even exclusively marine, and for the most part appear to be of shallow-water origin. They are comparable, in short, to the sediments now gathering off continental coasts at no great distance from the land. An immense succession of strata composed of such materials obviously must have been deposited upon a gradually sinking sea-floor. It would seem, therefore, that there must be a causal connection between crustal subsidence and sedimentation: either subsidence is the cause of continuous accumulation, or the crust must sag under a gradually growing weight of sediment.

The latter was the explanation suggested by Sir J. Herschell, who, assuming the existence of a subcrustal stratum of liquefied matter, contended that any changes in the incidence of pressure would induce contemporaneous movements of elevation and depression. The removal of rock-material from the land, for example, would cause the latter to rise, while the adjacent sea-floor, weighted with the transported material, would tend to sink. James Hall extended this view to explain the origin of the Appalachian Mountains and similar ranges, maintaining that great troughs or basins were caused by the gradual sagging of the sea-floor under a constantly increasing load of sediment. In the case of the Appalachians, the width of the basin just before the process of folding commenced probably exceeded 300 miles, while its greatest depth was some 40,000 feet. The downward movement, according to Hall, must have brought about a state of



VIEW FROM CLACH GLAS, ISLE OF SKYE.

[The two conical hills in the middle distance are Granite ; the rugged mountains (Coolins) in the background are Gabbro.]

Photo, Abraham, Keswick.

THE RED HILLS (GLAMAIG, ETC.), FROM GLEN VARRIGILL, SKYE: Morainic mounds in middle distance.

Photo, H.M. Geological Survey.

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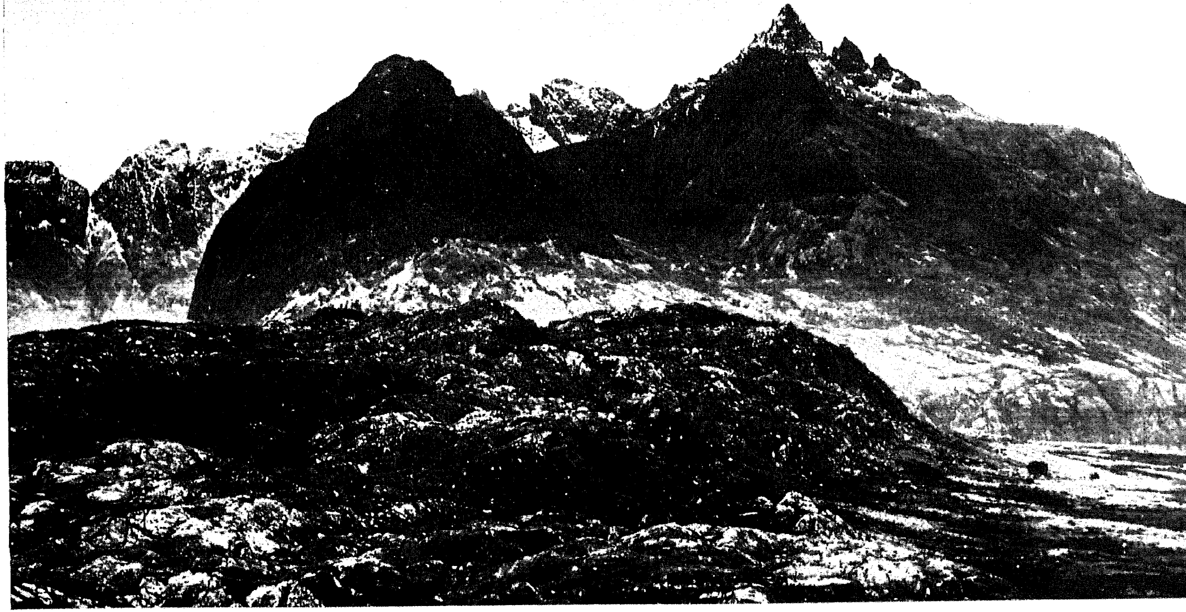
compression above and of tension below. Towards the bottom of the basin the down-bent strata would be rent and fractured, while the diminished width of surface above, caused by the sagging, would result in the strata being wrinkled and folded. But, as Whitney, Le Conte, and other geologists pointed out, when the immense extent of the Appalachian geosyncline is kept in view, one cannot fail to see that the concavity occupied by the strata was after all a relatively gentle depression. A series of strata 40,000 feet thick towards the middle, over 300 miles wide, and some 1500 miles in length, is proportionately a thin lenticular sheet. The degree of folding induced by the subsidence of such a relatively shallow basin must therefore have been insignificant, and quite insufficient to account for the extreme plication and the considerable displacements seen in the Appalachian chain. Hall was aware that his theory, while it accounted as he thought for the folding of the strata, left the elevation of the mountains unexplained: it is, as Dana remarked, "a theory of mountains with the mountains left out." It became necessary, therefore, to postulate another crustal movement, and to suppose that after the folding of the strata had been completed, the whole region was uplifted so as to form a wide plateau, out of which the existing ranges and valleys were subsequently carved by erosion. Other objections have been urged to James Hall's theory of the origin of mountains, but as it no longer finds supporters, we may leave it here.

One of his doctrines, however, has gained considerable acceptance, the doctrine, namely, that denudation induces elevation of the land, while concurrent sedimentation causes the sea-floor to sink. One cannot doubt that gravitation must tend to bring about a condition of equilibrium in the globe, so that if a rock-mass equal in bulk to the Alps could be lifted bodily from the land and placed upon the sea-floor, equilibrium would be disturbed and readjustment would follow, rapidly or more slowly, according to the nature or condition of the subcrustal layers. If liquid matter underlies a relatively thin crust, then the adjustment would probably be more or less rapidly effected; if, on the other hand, the globe be essentially solid throughout, equilibrium would only be attained very gradually. But mountains are not suddenly removed from the land, and dumped on the sea bottom: their degradation is a slow process, and the accumulation of a great thickness of strata must be no less protracted. It is doubtless probable that up and down movements would be the result of contemporaneous erosion and deposit, *if only the crust were sufficiently mobile.* Under such conditions the land, lightened of its load, might be expected to rise, while the sea-floor correspondingly weighted would tend to sink. In this way enormous thicknesses of shallow-water formations might come to be accumulated one above another in regular succession over the same area. It is hard to believe, however, that the crust is so very unstable. Enormously thick deposits, every one admits, are impossible in shallow water.



THE COOLIN MOUNTAINS (GABBRO), SKYE: SGÙRR NAN GILLEAN ON RIGHT, SGÙRR NA-H UAMHA NEAR CENTRE.

Photo, H.M. Geological Survey.

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Consequently if sedimentation be the cause of subsidence, the shallow sea-floor must begin to sink soon after accumulation has commenced, and subsidence must continue *pari passu* with sedimentation. But the crust cannot be quite so yielding, and most geologists are of the opinion, long ago held by Studer, the Swiss geologist, and stoutly maintained by Dana, that continuous accumulation is not the cause but the consequence of gradual subsidence.

Assuming then that submarine basins and troughs are due to independent crustal movements, and that it is their gradual development that makes the accumulation of thick masses of sedimentary strata possible, we have still to ask why those thick accumulations should apparently be so liable to compression. The gravitation theory advocated by Hall having been set aside, other explanations have been advanced. Among these is the so-called "expansion or thermal theory." Physicists tell us that the lines of equal earth temperature (isogeothermal lines) for some considerable distance downwards follow approximately the configuration of the surface, rising up under mountains, and curving down under valleys and other depressions. It is contended, therefore, that the accumulation of sediments in a great trough is equivalent to a local thickening of the earth's crust and must cause the geothermal lines to rise. The lower portions of a thick and growing succession of strata should in this way become affected by the heat of the interior. In the case of the Appalachians we have a thickness of 40,000 feet of rock; in other

words, the bottom of the elongated trough must have subsided to that extent. If the increment of temperature downwards be taken at the rate of 1° F. for every 50 feet of descent, we obtain a temperature of 800° for the bottom of the geosynclinal basin. It is quite possible, of course, that at some distance from the surface the rate of increase may diminish, or, as some have supposed, it may augment. But, whatever the truth may be, we cannot doubt that at a depth of 40,000 feet the heat must be great. Probably, too, the temperature may have increased downwards more rapidly in earlier geological ages than it does at present; and, if so, then the strata occupying the Appalachian basin may have been subjected to a considerably higher temperature than 800°. We can understand, therefore, that a highly elevated temperature would cause the rocks to expand, and this is the basis of the theory of rock-folding advocated by the late Mr T. Mellard Reade.

According to that theory the deformation of the strata filling a basin is due partly to the dilatation of the heated masses themselves, and partly to the expansion caused by the intrusion of igneous rocks. The compression produced in this way is internal, and proportional to the depth of the strata, and is thus concentrated along the major axis of the basin, where the bedded masses attain their greatest thickness. An anticlinal fold, according to Mr Reade, is first developed along this line, and thereafter fold after fold is compressed against it, and so the work of mountain-building proceeds. At the same time

SGÙRR NAN GILLEAN, SKYE. Showing the characteristic configuration of the dark gabbro which has invaded the Tertiary basalt plateaux of the Inner Hebrides, as a laccolitic Batholith.

Photo, H.M. Geological Survey.

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fused or semi-fused matter in the crust is forced up from great depths, chiefly along the axis of the growing chain, and this igneous matter expanding laterally forces back the folded strata which are thus still further compressed. At the same time the very presence of such molten masses must raise the temperature of the surrounding rocks, causing them to expand, and thus increasing the pressure. With a subsequent fall of temperature contraction would take place, but this would not entail the collapse of the mountains elevated by compression. On the contrary, according to Mr Reade, as soon as contraction supervened, the crust would be rent and fissured, normal faults or dislocations would come into existence, and the mountains would be wedged up by the irregular subsidence of great crust blocks.

Several objections to this expansion or thermal theory have been advanced. Professor Neumayr, for example, has pointed out that the explanation proceeds upon the assumption that the filling up of the basin was completed before heating and dilatation had commenced, whereas it can hardly be doubted that the geotherms would begin to rise soon after sedimentation had set in, and would continue to rise with the gradual filling up of the basin. If it be maintained that the rise of the geotherms could not have kept pace in this way with the growth of the deposits, we shall then be compelled to assume either a very rapid rate of sedimentation or an extremely slow rise of the geotherms, neither of which is probable. And even if such were the

case, a portion of the heat must nevertheless have been ineffective for the purpose required, seeing that the geotherms must have commenced to rise while the strata were still in process of formation, so that in this way some of the heat requisite for expansion must have been lost. Again, if we suppose that the strata did not begin to be warmed up until their formation had been completed, it is obvious that the lower beds in the basin must have been attacked long before the upper strata became affected. Had such been the case, we should expect to find some difference between the folds in the deeper and the higher parts of the structure. But no such difference or distinction is visible; on the contrary, the whole series of strata from bottom to top has obviously been folded and mashed together contemporaneously.

Another objection to the expansion theory was advanced by Dana, who argued that the expansion caused by a rise of the geotherms was inadequate to account for the amount of compression which has taken place. Mr Reade supposed that rocks upon an average would expand 2·75 feet per mile for every rise of 100° F. Applied to the case of the Appalachian Mountains, this would give a linear expansion of little more than one mile for two hundred and fifty miles, the present width of the area. The actual contraction produced by folding, however, is greatly in excess of one mile, having been estimated at forty-four miles, or even at twice that amount. In other words, were all the folds and

overthrusts of the Appalachians to be smoothed out, the width of the strata would probably exceed three hundred miles.

Dana further pointed out that the theory did not explain why the axes of the folds should all coincide with the longer axis of the basin. If folding were simply the result of rock-expansion, we should expect to find synclines and anticlines traversing the region affected in many other directions; for, as Dana remarked, "in a trough having the depth only a thirtieth or a fortieth of the breadth, expansion would act nearly equally in all directions." Other theoretical objections have been urged, but these we need not consider. It will be enough to remind the reader that the crustal movements to which all folded mountains owe their origin would seem to have been in each case unilateral, or in one direction only, and that no amount of rock-expansion caused by subterranean heat could have produced the extensive over-folding and the translation, sometimes for many miles, of enormous rock-sheets, which, as we have seen, are so characteristic of the Alps and the ancient Caledonides of north-west Europe.

The theory of mountain-making that finds most favour in our day has long been upheld by many of the most notable geologists of this and other lands. Dana, Le Conte, and their disciples in America, Suess, Heim, and numerous others in Europe, have consistently maintained the view that, as already indicated, folded mountains owe their origin to the sinking of the crust upon the cooling and contracting

nucleus. Le Conte, who adopted the view that mountain ranges are lines or zones of special accumulation, was of opinion that the great thickness of the strata would cause a rise of the geotherms, and thus tend to weaken the crust. Softened by subterranean heat the rocks would be in a condition to yield readily to compression, while the very process of crushing and folding would increase the temperature. Le Conte, indeed, considered it quite probable that a mountain range might be underlaid by a stratum of semi-fused or fused matter, which on cooling and solidifying would form a metamorphic or a granitic core. And this, he believed, was the origin of the schists and granitoid rocks so frequently exposed by denudation in the axes of great uplifts.

But the igneous rocks referred to do not always belong to the period of uplift. In many cases they are older than the deformation of the strata amongst which they occur, while in not a few chains and ranges igneous intrusions are either sparingly present or altogether wanting. Nor is there any evidence to show that the rocks of a great uplift were in a soft or semi-fused condition before folding had commenced So far as can be shown to the contrary they were probably, just before upheaval took place, as solid and resistant as rocks of like age and composition outside of the compressed area. That the rock-masses of a mountain chain have in many places behaved like plastic bodies is true enough; but that plasticity, as we have seen, was the result of the extreme compression to which they were subjected

PLATE LVIII.

THE BLAVEN RANGE, SKYE. [The upper and darker part of the picture is Gabbro, the lower and paler portion is Granite.]

Photo, H.M. Geological Survey.

during the mountain-making process. Under an enormous load the strata have been sharply folded and crumpled without breaking, but elsewhere, in the same chain when rocks of a like kind have been plicated under a lighter superincumbent weight, they have not become plastic so as to flow, but have been fissured, broken, and shattered. So again the foliated or schistose structure, so frequently characteristic of the rocks of a mountain chain, has undoubtedly been acquired during the compression and upheaval of the latter. In short, we find no evidence that would lead us to believe that any of the stratified rocks occurring in such uplifts have either been softened or fused and metamorphosed before they were finally compressed and buckled up.

From these and other considerations it would seem that the folding of strata in mountain uplifts cannot be attributed to a weakened condition of the rocks. Rather must it be assigned to the instability of the region in which the strata have accumulated. The most unstable areas of the crust appear frequently to have coincided with the line where, for the time being, continental plateau and oceanic basin met. But that is precisely the zone over which sedimentation is most active, and where, during gradual depression of the sea-floor, enormous and widely-spread sheets of littoral and sublittoral deposits may well be accumulated. It is conceivable, for instance, that numerous concealed geosynclinal troughs may underlie the marginal areas of the Atlantic basin. The only conspicuous coastal troughs

that we know of, however, are those which occur in many places round the borders of the Pacific. But these are obviously the result of independent crustal deformation, and are therefore not the kind of troughs imagined by James Hall and his followers. According to them the sea-floor slowly subsides under a gradually increasing load of sediment, subsidence and sedimentation proceeding *pari passu*. It is needless to say, however, that this is merely an ingenious hypothesis. No evidence has been adduced which proves that sagging of the crust is caused by such means. The only troughs, the existence of which is quite manifest, are those we have just referred to, and their very existence proves them to be of independent origin.

The sea-floor throughout extensive regions is gradually sinking, and not along marginal tracts only, although the latter, as already remarked, would appear to be exceptionally unstable. Protracted spasms of mountain-making have occurred within these zones, sometimes after the accumulation of a great thickness of strata, at other times after the deposition of relatively insignificant sheets of sedimentary materials. In the structure of certain polygenetic chains, we may read the history of several successive uplifts, separated by protracted periods or shorter intervals of erosion and accumulation. The labile or unstable zone would seem in such cases to have long retained its position. Again and again a broad belt of folded rocks has subsided in whole or in part, to be as often re-elevated, while younger

strata have been buckled up along its flanks, or even driven upward and forward over the denuded surface of the older ranges. In other cases, however, uplifts have been at once pressed against and overthrust upon the rigid or relatively stable continental plateau, and the zone of special instability has then shifted seaward. But while crustal movements have often been directed from the sea towards the land, they have, on the other hand, frequently been developed from the land towards the sea. In either case, of course, the continental plateau increases at the expense of the oceanic basin.

Probably there are no regions of the globe, the careful study of which promises to throw more light on the genesis of mountain uplifts and other cognate phenomena than the coast-lands of the Pacific Ocean, and the great basin itself with its remarkable "deeps" and multitudinous islands. Here, if anywhere, geologists may be expected to acquire more definite knowledge of any relation that may obtain between uplifts, subsidences, and volcanoes. As the phenomena referred to are abundantly displayed, and their latest developments belong to a relatively recent date, some brief account of the Pacific region may not be without interest.

CHAPTER XI

ORIGINAL OR TECTONIC MOUNTAINS—*continued*

Leading Geological Phenomena of the Pacific Ocean and its Coastlands. The Margin of the Oceanic Basin and Continental Plateau. Depths of the Ocean—Coastal and Central "Deeps." The Mountain System of Asia. Islets of Oceania. Professor Suess's Theory of "Foredeeps." Presence of Certain Foredeeps and Absence of Others not explained by the Theory. The Pacific Basin a Sinking Area. Probable Origin of the "Deeps," and the Volcanic Phenomena of the Sea-floor and Coastal Ranges of Asia and America.

GEOLOGISTS and geographers have long been agreed as to what are the outstanding features of the lithosphere. They have no difficulty in distinguishing an elevated portion over which the continents and larger islands are distributed, and a more extensive, flat, basin-like depressed area occupied by the ocean. To this depression, however, the waters are not confined, for relatively shallow seas invade the less elevated parts of the land-bearing region. In other words, considerable portions of the true continental area are submerged. This elevated although partially submerged region of the lithosphere is termed the "continental plateau," while the more depressed portion is known as the "oceanic basin." Through-

out the geological past many modifications have been effected in the form and extent of both areas, but we have no reason to believe that the two have ever changed places. As the earth is a cooling and contracting body, subsidence must obviously have been the dominant movement of the crust, necessarily affecting both continental plateau and oceanic basin, but reaching its maximum in the latter. The oceanic basin, therefore, has in the course of time become more contracted, and is probably deeper now than ever before, while the continental plateau is probably more extensive, and dry land more continuous than in earlier ages.

The coasts of our existing continents nearly coincide in some tracts with the margin of the continental plateau: in other regions they retire from that margin for great distances. In the former case they show a regular outline, long inlets of the sea are of infrequent occurrence, and fringing islands rarely appear. In the latter case, however, the coast-line is extremely irregular, inlets large and small are numerous, while fringing islands usually abound. The descent from the margin of the continental plateau to the oceanic basin within the Pacific area is generally abrupt. Along the west coasts of South and North America, for instance, the sea-floor shelves more or less gently until a depth of 100 fathoms is reached, and then it plunges down steeply to 500 or even 1000 fathoms or more before it begins to flatten out. Deep water, in short, is reached along the whole west coast of the Americas,

at no great distance from the land. Very different conditions obtain along the coasts of Asia and Melanesia. In those regions the continental plateau is so extensively submerged that only in Kamchatka does the coast of the mainland approximately coincide with the margin of the former. In the far north that margin is bounded by the Aleutian Islands, whence it follows the coast of Kamchatka and the east coasts of the long festoons of islands that extend southward by the Philippines to Tulur Island. After this it is difficult, owing to the manifold irregularities of the sea-bottom, to trace any distinct line of separation between continental plateau and oceanic basin. It must be drawn outside of Melanesia, however, for New Guinea, the Admiralty Islands, Bismarck Archipelago, the Solomon Islands, New Hebrides, New Caledonia, and the Fiji Islands all belong apparently to the continental plateau. The line of demarcation we are looking for again becomes recognisable between Fiji and the Samoa Islands, the edge of the continental plateau forming a well-marked feature that extends south-south-west in a nearly straight direction, from a point some 50 miles south of Samoa, towards the north-east corner of New Zealand, a distance of about 1150 miles. For our present purpose it is unnecessary to follow it farther.

The oceanic basin within the Pacific sinks to an average depth of 2400 fathoms or thereabout. Throughout very extensive areas it is approximately level or broadly undulating. This is markedly the

case beyond the Oceanides, or throughout what may be termed the American section of the basin. Within the region of the Oceanides its surface is naturally less monotonous. Could the water be removed we should see many isolated peaks, sporadic groups of mountains, and now and again abrupt mountain ridges traversing the wide flats of that region in a general north-west and south-east direction. In the far north the continental plateau would be observed rising steeply as a pronounced escarpment in front of what are now the Aleutian Islands. The long festoons of islands, extending from Kamchatka south-west and south as far as Tulur Island, a distance of 4000 miles, would similarly be flanked by great escarpments. Between Tulur Island and Samoa, however, the plateau would probably appear less conspicuous, declining gradually to the floor of the basin. From Samoa south to New Zealand the escarpment of the plateau would again come prominently into view. On the American side of the basin an equally conspicuous escarpment, as already indicated, would overlook the depressed floor of the basin along the whole extent of the double continent from Alaska to the extreme end of South America.

The Pacific, as every one knows, is in places much deeper than 2400 fathoms, depths of over 5000 fathoms having been sounded. Of these "deeps," as they are called, there are two kinds, which differ from each other especially in form and distribution. One kind is essentially trough-shaped

and confined to the marginal zone of the oceanic basin; the deeps of this type, in point of fact, trend along the base of the escarpment of the continental plateau. Here it is that the greatest depths of the ocean are met with. The cross-section of those marginal troughs is essentially the same everywhere, the South American deeps being identical in shape with those of the northern and western borders of the Pacific. The latter, however, are not only somewhat deeper, but longer and more continuous. On the accompanying map (Plate LIX) a section (Fig. 1) across the Pacific from Japan to North America shows the Tuscarora deep of the great Japanese Trough. It will be observed that the sea-floor descends from the coast at a somewhat high angle to the depth of 4600 fathoms, after which it rises with a much gentler gradient until the level floor of the ocean is reached at a depth of a little over 2000 fathoms. The deepest part of the trough, therefore, lies relatively close in shore or at the foot of the continental escarpment.

The bottom of the Aleutian Trough is somewhat irregular, varying in depth from 3000 to 4000 fathoms. It extends from the Alaskan Peninsula along the whole front of the arc of islands, and is almost continuous with the enormous Japanese depression. The latter skirts the outer coasts of the Kurile Islands, Japan, and the Bonin Islands, with a depth ranging between 3000 and 4600 fathoms, the deepest part of the trough throughout its whole extent lying nearest the land. South of the Bonin Islands the festoon of the Mariana or Ladrone Islands is simi-

larly fringed on the east by another trough, in which depths between 3000 and 5000 fathoms occur. The Philippine Trough begins opposite the Riu Kiu Islands, and extends along the whole eastern margin of the Philippines to Tulur Island, at a depth of 3000 to 4700 fathoms, the greatest depths, as in all other cases, lying closest in shore. No trough appears in front of any of the northern islands of Melanesia between Tulur and Fiji. But we again encounter a very elongated depression—the Tonga-Kermadec Trough—stretching between the Samoa Islands and the north-east corner of New Zealand, the greatest depths of which range from 4000 to 5600 fathoms (see "Aldrich Deep" in the section, Fig. 2, Plate LIX).

Along the west coast of the Americas, troughs are hardly so notable in extent and depth as those on the other side of the ocean. The most remarkable are the sinks that occur at intervals close in shore between Callao and Valparaiso. These consist of an elongated series of troughs, or of one greatly extended trough of irregular depth, the depths nearest to the land varying from 2500 to upwards of 4100 fathoms (see Map, Fig. 2). No deeps of any importance have been charted along the west coast of North America, but deep water, as already remarked, is met with at no great distance from the shore, the sea-floor after a short interval suddenly sinking to depths of 1000 fathoms or more (see Map, Fig. 1).

It will be observed that the depressions now described are all connected with the margin of the

continental plateau: they occur either along the coasts of existing continents (South America, Alaska, Kamchatka), or along those of continental islands (Asiatic island-festoons). There is yet another kind of deeps of which mention must be made. These, unlike the troughs, have no connection with the margin of the continental plateau, but are characteristic rather of the central part of the oceanic basin. The majority occur west of meridians 150 and 160 west; but as large areas of the ocean have been only partially sounded, similar depressions may yet be discovered elsewhere. The deeps in question are not narrow, elongated troughs like those that skirt the base of the continental plateau, but broad, flat-bottomed basins of irregular form and often of great extent, as a glance at the map will show. They range in depth from 3000 to 3800 fathoms, and thus lie some 600 to 1400 fathoms below the general level of the ocean-floor (see Map, Fig. 3).

Before attempting to discuss the origin of the deeps of the Pacific, it will be necessary, in the first place, to consider very briefly the more notable geological features of the lands which are bordered by troughs. The latter are so frequently associated with a certain geological structure, that a causal connection between the two is at once suggested. Professor Suess, the distinguished geologist, believes that there is such a connection, that the troughs are characteristic accompaniments of folded mountains, and that those of the Western Pacific came into existence at the same time as the young uplifts that girdle the ocean

in that region. It may be of interest, therefore, to consider this theory with some attention ; and for this purpose we shall first take a rapid glance at the chief orographical features of Asia, for it would seem as if the theory in question had been suggested to its able author by his study of the physical geology and geography of that continent. Professor Suess's conception of mountain development is founded on so wide a range of evidence, and explains so many phenomena, that it must to a large extent be true. Geologists who may not accept it in its entirety will, nevertheless, admit its suggestiveness, and recognise its author's comprehensive grasp of a complex and difficult subject. Nothing can be more convincing than the picture he has drawn of the gradual evolution of the mountains of Asia. He introduces us first to a very ancient tract, named by him "Angara Land," which had been rendered stiff and rigid by compression before Cambrian times. This primeval land—the nucleus of the continent—extended from the far north down to the vicinity of Irkutsk, and it was around its southern outskirts that crustal compression caused the earliest Asiatic mountains to appear. These horseshoe-shaped or arcuate ranges were the first and therefore the innermost of many similar mountain-arcs, which at long intervals of time were successively uplifted farther and farther away from the heart of the continent. Towards the east we traverse these concentric arcs, one after another, until we reach the great island-festoons off the Asiatic coast. Towards south and south-west the grand

succession of uplifts terminates in the gigantic Himalayas, and the long series of ranges that extend into Europe. In all these chains the unilateral crustal thrust which brought them into existence has been persistently outwards from the interior of the continent, that is, east, south-east, south, and south-west.

The youngest uplifts on the Pacific side are represented by the great island-festoons just mentioned, and as the profound coastal troughs lie in front of these youngest mountains they are termed "foredeeps" by Suess. He shows that the long mountain-arc constituting the island-festoons exhibits a definite serial order of elements. The first element, on the outside or convex side of the arc, is the foredeep; then follows a belt of Tertiary deposits, often disturbed and folded. To this belt succeeds a concentric "cordillera" or ridge, or series of ridges, of older rocks which are folded to the east, that is, towards the oceanic basin. Lastly comes the volcanic arc, which is confined to the folds of the cordillera, no volcanoes ever occurring in the foredeep. This series of elements is sometimes incomplete but never inverted. The cordillera, for instance, may be wanting, but the volcanoes, active, dormant, or extinct, are rarely absent.

Dana long ago thought that the scattered islets of Oceania are the crests of submarine ranges, and Professor Suess is of the same opinion. He tries to show that the structure of the Asiatic festoons is repeated in them. But that is true only of the islands that pertain to the continental plateau.

Outside of that plateau, in the true oceanic basin, the islets appear to be entirely devoid of the "cordillera element." Some of them show limestone which is probably of Cainozoic age; many are volcanic, while a large number consist of recent coral above and no one knows what below. The linear direction of many of the island groups is certainly suggestive, and one cannot doubt that they are really mountains. But whether all or any of them are the result of crustal thrust from the direction of Asia, and built on the same plan as the island-festoons that fringe the Asiatic coast, seems more than doubtful. The majority rise abruptly from considerable depths, and, so far as one can judge from the soundings, are suggestive rather of volcanic forms than folded mountain ranges. The linear and curvilinear arrangements of certain island-groups do not necessarily indicate uplifts like those of eastern Asia. Volcanoes, as every one knows, are often similarly aligned, although not infrequently they may be grouped irregularly, or occur sporadically, each soaring above its surroundings in solitary majesty. As the islets of Polynesia are distributed in very much the same way, the probabilities are strongly in favour of their volcanic origin.

Foredeeps, according to Suess, would seem to be of the same age as the ranges in front of which they occur. His account of their origin, however, is perhaps not quite so clear as it might be: at all events one has some difficulty in realising exactly what he means. He refers with approval to Supan's

conjecture that the troughs are connected with foldings, remarking that "it is indeed obvious that this is the case."[1] He states further that the depressions in question "mark the subsidence of the foreland beneath the recent folds," but is careful to note that the foredeeps are not synclines in the tectonic sense of the word, for one side belongs to the foreland, the other to the folded mountains. In another place he remarks that "if we could remove the hydrosphere, a vast land would lie before us at a depth of 3600 to 4000 metres below the existing sea-level, but in front of the folded arcs [*i.e.* the Asiatic island-festoons] we should see elongated strips of land, no doubt not completely regular, which would lie 2000, 3000, or even 5000 metres lower than the vast tract of newly exposed land. This great tract of land is the foreland. *The outer border of the foredeep is the arcuate border of a subsidence of the lithosphere, and the inner border of the foredeep is the outer border of the folded range* which has advanced from the direction of the land over this deep."

It is difficult to reconcile these several statements. From one of them we are led to infer that the foredeep is a downward bend of the crust caused apparently during the advance of the folded range, and we picture to ourselves a range slowly advancing, the foreland at the same time subsiding beneath

[1] The quotations are from *The Face of the Earth*—the English translation of Professor Suess's monumental work, *Das Antlitz der Erde*—vol. iv., pp. 295, 505. The corresponding pages of the original are Bd. iii. 2, pp. 335, 336, 581.

and in front of it. But as some of the foredeeps are 20,000 to 33,000 feet in depth, or 5600 to 18,600 feet below the general level of the ocean-floor, we can hardly suppose that depressions so great can be downfolds of the same age and origin as the mountains. If such were indeed their origin, then we should expect the depth and extent of the depressions to bear some relation to the size and height of the islands behind them. But the soundings on the charts clearly prove that such is not the case. The deepest depressions do not always lie in front of the largest and loftiest islands, nor are the less important deeps associated only or chiefly with the smaller islands. No doubt Professor Suess recognised these facts, and knew that his foredeeps could not be accounted for by ordinary mountain-folding. This is probably why he considers the outer border of these foredeeps to be the margin of a great depression that affected all the region lying in the direction of Asia —"the subsidence was the primary phenomenon." It was over that subsided area that the mountains are supposed to have advanced from the west, but, strange to say, all stopped short at practically an equal distance from the margin of the great downfold or steep front of the "foreland." Why should they have done so, and why should the front of the mountain-arc and the "arcuate border" of the supposed subsidence be so exactly concentric? And what about the enormous Tonga-Kermadec Trough? Are we to surmise that here also a mountain range has advanced from the west over a deeply depressed

area of the sea-floor, and mysteriously stopped, like all the ranges of the Asiatic island-arc, just before it reached the outer border of the imagined subsidence?

There is another question which will be hard to answer. The islands of Melanesia represent, according to Professor Suess, an Australian system of more or less concentric mountain-arcs, all of which are folded over to north-east. The evidence, although not so complete as could be desired, certainly favours that conclusion. The Australian arcs confront the oceanic basin in the same manner as the arcs of Asia; but where are the foredeeps which ought to occur in front of at least some of these Melanesian islands, if the theory under consideration were true? *The soundings on the charts show that no deeps are there.* It may be said that the outermost and youngest of these Australian arcs may be of Mesozoic age, and much older therefore than the island-arcs of Asia, and that any foredeeps which might at one time have existed may now be masked or concealed by marine sediments. But that cannot be the true explanation, for the great Tonga-Kermadec-New-Zealand ridge (inferred by Professor Suess to be a range folded towards the east) is at least as old as any of the outermost arcs of Melanesia, and yet it is flanked by one of the deepest troughs of the Pacific (see Map, Fig. 2).

The mountain uplifts that constitute the Asiatic island-festoons, as we have seen, are all relatively young—they are of Tertiary age. Folded mountains of approximately the same age occur elsewhere, and

we may ask, therefore, if foredeeps occur in connection with these. Professor Suess believes that they do. He refers, for example, to the Persian Gulf, which he looks upon as the foredeep of the Iranian Mountains; while he recognises the foredeep of the Andalusian Mountains in the valley of the Guadalquivir. Neither the one nor the other, however, is at all comparable to the troughs of the Western Pacific, even when all allowance has been made for silting-up. In other cases cited, the occurrence of foredeeps is purely conjectural and cannot be proved. The delta of the Tigris and Euphrates may occupy a depression, and so likewise may the delta of the Ganges and the Brahmaputra, but we do not know that this is true, it is only an inference. If masked foredeeps are actually present in either region, all one can say is that they must be relatively insignificant as compared with the profound deeps of the Pacific. And the same remarks apply equally to the Alps and the Carpathians, in front of which great subsidences are supposed by Suess to be concealed beneath thick sheets of marine Cainozoic deposits. If the depths of these problematical foredeeps be at all proportionate to the dimensions of the mountains behind, they should be measured by many thousand feet. But who can believe that the young Cainozoic deposits of central Europe can even distantly approach so great a thickness?

Professor Suess is careful, however, to point out that foredeeps do not in all cases occur: some mountains, he remarks, have gradually flattened out and

therefore never possessed foredeeps. He has further suggested that foredeeps might occasionally have been obliterated by the advance of a folded range. "All such ranges," he says, "impelled by the general struggle for space, have a tendency to enter into the subsidences . . . or to overthrust the subsidences, or to throw the subsidences themselves into folds."[1] So that if the Asiatic island-arc throughout its length had only advanced equally for a few miles further, the deep concentric troughs that now exist would have been closed up or obliterated!

While foredeeps are neither characteristic, necessary, nor essential accompaniments of folded mountains, and can be otherwise explained, it must be admitted that subsidence of the crust may frequently have been caused by mountain-building. One can hardly doubt that considerable sagging must have taken place under the weight of such heaped-up rock-sheets as constitute the bulk of the Alps and other great chains. These mountains, it should be remembered, do not consist exclusively of strata folded and buckled up *in situ*. Folded and convoluted strata are no doubt always present, but most ranges seem built up largely of enormously thick rock-sheets which have been driven forward, often for considerable distances, and piled one on top of another. The heaping of all these stupendous rock-sheets to a height of probably not less, in many cases, than 10,000 or even 15,000 feet must have had some effect in depressing the area

[1] *Das Antlitz der Erde*, Bd. iii. 2, p. 722; English Translation, vol. iv., p. 627.

invaded: not only broad foredeeps, but similar backdeeps also might have come into existence. It is further not improbable that if volcanoes were subsequently developed in such a range, the amount of deep-seated molten matter eventually transferred by them from below might augment any subsidence due to the weight of the travelled and uplifted rock-masses. But however notable might be the depressions caused by mountain-building and volcanic accumulation, the deeps of the Pacific borders are nevertheless far too extensive and profound to be thus accounted for.

A stronger argument against the validity of Suess's theory remains to be stated. That theory impresses one at first sight as plausible and logically consistent. All the foredeeps of the Western Pacific lie immediately in front of folded ranges—there is, apparently, no exception to the rule. Were attention confined to the Asiatic side of the ocean, or did coastal deeps occur nowhere else, we might feel justified in looking upon such depressions as one of the normal accompaniments of mountain ranges. Unfortunately for the theory, however, deeps of precisely the same character as those of the Western Pacific are strongly developed along the west coast of South America, where, according to Suess, their presence is quite inexplicable. The mighty ranges of the Andes, it must be remembered, are all folded and overthrust towards the east; along the whole extent of coast the crustal movement has been directed from the oceanic basin against the continental plateau.

The troughs that follow the coast-line, therefore, are not *foredeeps* but *backdeeps.* And yet, as the charts show, these backdeeps are in all respects similar to the foredeeps of the Western Pacific. Surely a theory that professes to explain the Asiatic troughs, but does not account for their South American counterparts, must be considered unsatisfactory.

Careful scrutiny of the evidence leads one to the conclusion that all the coastal troughs of the Pacific without exception are of the same age and origin. They seem to have come into existence at a relatively recent date, and may well have been increasing in depth up to the present. The uplifts that practically girdle the Pacific are of Cainozoic age; the coastal ranges, at least, do not date further back. Certain uplifts may have commenced somewhat earlier than others; but from a broad point of view they may all be considered contemporaneous, for the grand crustal movement to which they owe their origin was general, affecting the whole east and west borders of the Pacific throughout a long period of time. The thrust from the side of Asia was pronounced, resulting, as we have seen, in the formation of the great island-arc. That thrust came from north-west and west. Along the Melanesian border of the continental plateau, however, the crustal movement was directed towards north-east, but it is not quite clear whether that movement took place in late Tertiary times or somewhat earlier. And the same may be said of the Tonga-Kermadec-New-Zealand "range," the folding of which indicates a thrust towards the east. From

Patagonia up to and beyond California, all the coastal uplifts bear witness to a powerful easterly thrust having occurred in late Cainozoic times. Thus one may say that the latest unilateral movement within the Pacific area has been from north-west and west to south-east and east, that is, *on the Asiatic side, away from the continental plateau* towards the oceanic basin; *on the American side, from the oceanic basin* against the margin of the continental plateau.

The geology of the great chain of the Andes is still very imperfectly known, but all the ascertained facts conspire to assure us that the formation of the mountains commenced long before the Cainozoic era, in Mesozoic or even earlier times. The process of mountain-building was interrupted now and again by prolonged intervals of repose. This polygenetic chain measures some 250 to 550 miles across, and is of the same type as the Alps and similar folded mountains, consisting as it does of a complex of convoluted strata and translated rock-sheets of great extent and thickness. According to Professor Heim the area presently occupied by the European Alps, which are not more than 150 kilometres in breadth, formerly existed as a flat land, probably measuring 600 to 1200 kilometres across. Now, if the Andes have resulted from compression in a like degree, it is obvious that a very considerable strip of ocean-floor must have been buckled up and added to South America.

The southern extensions of the Rocky Mountains and the Californian ranges tell a like tale of long-continued mountain-building, extending from Meso-

zoic down to late Tertiary times, the crustal thrust having been directed, as in the case of the Andes, persistently from the west. Thus, along the eastern borders of the Pacific we have evidence of a considerable diminution in the width of the oceanic basin.

Comparing the American ranges with the corresponding arcs of eastern Asia we note certain broad contrasts. The latter are neither so lofty nor so closely packed as the former. A more or less broad space separates one concentric arc from another. For instance, the youngest prominent arc—that of the island-festoons—is divided from the chains lying to the west by the epicontinental seas of Ochotsk, Japan, and China. On the American side of the ocean, on the other hand, all the compression has been concentrated within a comparatively narrow zone along the margin of the continental plateau.

The formation of all these chains, Asiatic and American, carried on through a vast period of time, would necessarily relieve the crust within the oceanic basin, and thus facilitate the sinking of the sea-floor. It is not surprising, therefore, that after the latest considerable uplifts of Cainozoic times, a general movement of depression should have set in. The subsidence of the crust in the oceanic basin would induce strain and tension along the borders of the stiffened or relatively rigid continental plateau. In some places this might result in merely bending down the margin of the latter, without producing any considerable fracturing of the crust. In other regions, however, where the crust had been thickened and

rendered more rigid by compression, the strain and tension caused by the sagging of the sea-floor would be relieved by faulting. Strongly marked dislocations might therefore be expected to take place in front of the newly-formed Asiatic arcs, and along the borders of the stiffened continental plateau on the opposite side of the ocean. This is in all probability the origin of the great deeps of the Pacific. The nature of the dislocations can of course only be conjectured. The descent from the coast to the bottom of a trough, although relatively rapid, does not suggest an ordinary or normal fault—the declivity is not steep enough to be described as a cliff. No doubt the troughs, as shown upon the map and accompanying sections, appear to be quite close to the shore and to have vertical or nearly vertical sides. But that is owing to the small size of the map, and to the fact that the vertical scale of the sections is greatly in excess of the horizontal. In reality the deepest part of a trough is sometimes eighty miles or more beyond the coast-line. When drawn upon a true scale, therefore, the deeps no longer appear as vertical-sided troughs. The descent from the land to the bottom of a trough, although relatively steep, is not such as to indicate the presence of a normal fault, but rather of a series or succession of step-faults. Not improbably, indeed, many of the troughs may be true geosynclines. The rise of the sea-floor from the trough to its outer border is usually at a much lower angle than the descent from the land, and the deepest part of the depression, therefore, lies

much further from its outer border than from the coast-line.

A glance at the map shows that "deeps" of all kinds are more abundantly developed in the Asiatic than in the American section of the Pacific; and the same holds largely true as to the distribution of islets outside of the true continental plateau, most of which pertain rather to the Asiatic and Australian than to the American side of the ocean.

When an area so extensive as the Pacific basin began to subside between rigid or practically immobile borders, it would hardly do so with perfect regularity. Subsidence would result in warping the sea-floor, and so producing broad undulations and depressions. Such would seem to be the origin of the central deeps which sink from 3600 to 8400 feet, or more than one mile and a half, below the average level of the ocean bottom (see Map, Fig. 3). This unequal sagging of the crust must have tended to diminish the width of the upper crustal layers, and may therefore have had some influence in the formation or modification of the coastal troughs. Probably also the strain and tension caused by unequal sagging would result in rents and fractures of the sea-floor, up through which molten matter would escape, and thus give birth to the chains and groups of volcanoes which now form the numerous islets of Oceania. But why subcrustal activity should have been more pronounced in the western than in the eastern section of the basin we do not know. Possibly the relative degree of depression

within the two areas may have had something to do with the phenomena, especially with the distribution of volcanoes. The average depth of the ocean has been given as approximately 2400 fathoms, and there are few parts in the western section of less depth, except near islands. In the American section, on the other hand, extensive areas do not much exceed 1500 fathoms in depth. On the whole, therefore, the Asiatic section is the deeper of the two.

Apart from the evidence of dislocation supplied by the coastal deeps, the soundings round the margin of the Pacific basin are almost everywhere suggestive of faulting; the whole ocean floor seems to be subsiding between engirdling dislocations. The descent from the coast is in some places so abrupt that the declivity would appear to indicate the presence of normal faults. In other tracts, however, the descent is less sudden, and suggestive rather of step-faults, or possibly of simple down-bending or monoclinal folding. It is interesting to note that many years ago Richthofen expressed the opinion[1] that the Pacific basin was bounded by great step-faults, but I am not aware that he ever set forth the facts that led him to that conclusion.

We do not know how thick the crust is, and can only conjecture what the nature of the subcrustal materials may be. Not improbably, as many geologists suppose, the crust passes downwards into a viscous, semifluid, or fluid magma. If such conditions obtain, then the pressure exerted by the

[1] *Fuhrer für Forschungsreisende* (1886); Neudruck, 1901, p. 594.

subsiding crust might be expected to force the mobile magma aside. It should be squeezed outwards underneath the uplifts forming the marginal zone of the continental plateau, where it would escape from pressure by rising into the more or less vertical fissures by which all uplifts of the kind are traversed. Not unlikely this may be the reason why volcanoes are so abundantly distributed along the mountains that girdle the Pacific. The molten matter is simply forced upwards by the subsiding crust. The supposed subcrustal conditions would also serve to explain why volcanic action should not be developed in the coastal deeps, for the walls of the faults leading down from those troughs are possibly at great depths kept in such close apposition as to prevent the escape of molten matter to the surface.

These great marginal dislocations have been referred to as if they were singular. It is highly probable, however, that the ocean-floor is traversed by many others. Judging by what we know of the large faults traced in our own and other countries, it is likely enough that the marginal dislocations that divide the oceanic basin from the continental plateau are accompanied at less or greater distances by numerous smaller parallel faults, along which movement may take place in the same way as along the major dislocations. It is doubtless movements of the kind that are the cause of the many destructive earthquakes which so frequently visit the coast-lands of South America, most of these earthquakes apparently originating under the sea.

The broad deeps distributed chiefly over the central part of the Pacific basin have been ascribed to the irregular settling down or sagging of the crust. Possibly also internal compression, caused by irregular movements of the kind, may have been relieved by local uplifting, and the formation of occasional wrinkles or ridges, some of which may have reached considerable heights above the average level of the sea-floor. The fact that some of the islets of Oceania give evidence of recent elevation, would thus seem to show that wrinkling and up-swelling of the crust may occur here and there within an extensive area undergoing depression.

Some geologists imagine that an ancient continent lies drowned in the Pacific, a notion in support of which no evidence can be cited. It is nothing more than a conjecture, suggested apparently by the exigencies of a certain theory. According to that theory the sediments of Mesozoic and Cainozoic times have been accumulated in immensely elongated geosynclinal troughs, one of which is represented as having circled round the Asiatic and American borders of the Pacific area, so as to catch the waste-products washed down from an imaginary central continent. Although it is not possible to demonstrate that the Pacific Ocean is of primeval antiquity, yet all the phenomena seem to favour that conclusion, and to negative the idea of a great Pacific continent such as the geosynclinal theory desiderates. The configuration of the sea-floor, so far as soundings reveal it, is not that of a land-surface. The long coral-

crowned ridges that here and there traverse the basin can hardly be other than volcanic, formed in the same way as the elongated ridge of the Sandwich Islands is forming now. The solitary islets and irregular groups of islets are all similarly suggestive of a volcanic origin.

While admitting that the islets in question are most probably volcanic, certain geologists think they may rise from the backs or shoulders of great mountain uplifts. This view has obviously been suggested by the well-known fact, that all round the Pacific basin volcanoes occur only among the encircling cordilleras. But in other regions, it need hardly be said, volcanoes are not always perched upon the backs of mountain uplifts. Etna and Vesuvius began their eruptions on the sea-floor, and there are numerous examples of recent submarine volcanoes, some of which have remained below water, while others have become subaerial. All considerable volcanoes have originated on lines of fracture, either within a sinking area or in the adjacent rigid or relatively immobile tract, usually near but sometimes further away from the borders of the subsidence. It is not the configuration of the surface—which may be mountainous and lofty, or low-lying and plain-like—but the presence of suitable lines of fracture that determines the appearance of volcanoes within or immediately outside of a sinking area. As no trace of Palæozoic or Archæan rocks has been detected in any of the islets within the true oceanic basin—the only rocks visible being either of organic or volcanic origin—it seems reasonable

to conclude that these islets represent the tops of volcanoes and volcanic ridges built up from the floor of the ocean upon lines of fracture. There is nothing in their arrangement, or want of arrangement, at all events, that militates against that conclusion. One might well expect, indeed, that a broad expanse like that of the Pacific basin should here and there be rent and fissured while it subsided, and that molten matter should rise through such fissures, and build up in time sporadic, isolated volcanic mountains, or lines of volcanic islands like those of Hawaii.

The flatness of the sea-floor may be original, but it may well be also to some extent the result of sedimentation. In the earlier geological ages the oceanic basin probably attained no such profound depths as at present, and under those conditions currents must have played a more important rôle as carriers and distributors of sediment. It is conceivable, therefore, that even the central parts of the Pacific may be paved with Palæozoic sediments, while Mesozoic and Cainozoic deposits may extend far outwards from the borders of the continental plateau.

While considering the great deeps of the Pacific, it is hardly possible to avoid a brief reference to those of the Indian Ocean. The eastern coasts of that ocean are undoubtedly of the Pacific type, and troughs seemingly of the same character as those of eastern Asia skirt the coasts of Java and Sumatra. All the appearances, in short, indicate that a movement of depression similar to that of the Pacific is in progress in the region referred to.

Having endeavoured to show that foredeeps are not a characteristic accompaniment of folded ranges, notwithstanding their appearance in front of the Asiatic island-arcs in the Pacific and Indian Oceans, we should like to point out that backdeeps occur even more frequently in connection with folded ranges. It would seem as if a period of crustal compression was not infrequently followed by partial crustal collapse. Witness, for instance, the long string of epicontinental waters lying behind the latest uplifts of the Asiatic arcs from Bering Sea south to the East Indian Archipelago. Consider also the similar depressions met with in other regions of recent mountain uplift, such as those of the Caribbean Sea and the Mediterranean. We might even point to the broad valley of the Po, and the extensive Hungarian plains, as not improbably concealing backdeeps of a more pronounced depth than any foredeeps that may possibly lie below the young Cainozoic deposits spread out in front of the Alps and the Carpathians.

From all that we know of crustal movements, it may be inferred that the marginal deeps of the Pacific basin have been gradually developed, that the formation of these troughs has not been more rapidly effected than the uplifting of mountain ranges. If this be a reasonable conclusion, why, it may be asked, have they not in all cases been obliterated by sedimentation? The explanation is obvious, as a glance at the map will show. The most continuous and deepest depressions, it will be noticed, are ranged in

the north and west along the margin of the great island-arcs, from which the discharge of sediment is relatively insignificant, and therefore never could have kept pace with the development of the deeps. No doubt many large rivers bring down enormous quantities of sediment from Asia; but all that mud is deposited in the epicontinental seas, none of it can possibly enter the marginal troughs. Along the west coast of South America the conditions are not very dissimilar. The rivers descending from the Andes doubtless transport much sedimentary material, much more, indeed, than can possibly be derived from the island-arcs of Asia. But they have no long distance to flow; as carriers of the waste products of the land, therefore, they are relatively of little importance. Since coastal deeps put in a strong appearance here and there off the coast of South America, it is quite clear that in those regions sedimentation has not proceeded *pari passu* with depression. The drainage conditions of the Pacific sea-board of North America do not differ greatly from those of the corresponding regions in the southern continent. The coast ranges send down no large streams, and few considerable rivers with extensive catchment areas enter the sea along the whole long coast-line. It is obvious, therefore, that if troughs comparable in importance to those of the Western Pacific had been developed anywhere between Alaska and Panama, they could hardly have been simultaneously obliterated by the limited amount of sedimentation there taking place. Since no troughs seem to be present, we may safely

infer that none ever existed ; and thus we reach the conclusion that a subsiding sea-floor is not necessarily margined throughout by trench-like depressions.

We have referred to the occurrence in the Indian Ocean of deeps that skirt the coasts of Java and Sumatra. Another elongated depression, it may be pointed out, appears off the west and south coasts of Australia. These subsidences would seem to have remained manifest for the same reason as the great troughs of the Western Pacific. They have been developed opposite lands not watered by large rivers draining extensive areas, and consequently in their case sedimentation has not kept pace with subsidence.

Turning our attention to the Atlantic basin, we are at once struck by the almost complete absence of coastal deeps. The only profound depressions of the kind are those that flank the outer islands of the West Indies. They are conspicuous there doubtless for the same reason that the similar troughs of the Pacific and Indian Oceans are still manifest—they lie in a tract of minimum sedimentation. Elsewhere, however, we search the charts in vain for the appearance of marginal troughs along the coasts of the Atlantic. Yet it is hard to believe that phenomena which are so marked a feature of the Pacific should not likewise have been developed to a certain extent on one or the other side of the Atlantic basin. But when we remember that nearly the whole drainage of the Americas, together with a considerable proportion of that of Europe and Africa, is discharged into the Atlantic, we cannot but suspect that coastal deeps may

really be present, and that active sedimentation may well account for their apparent absence. Had any depressions of the kind been slowly developed along the east coast of South America, for instance, it seems most unlikely that they should ever have been revealed. The distribution of sediment proceeds so rapidly in that region that gradually developing troughs could hardly escape being obliterated; and as similar conditions obtain throughout vast reaches on both sides of the Atlantic, we need feel no surprise that coastal deeps have not been detected.

Since the primeval configuration of the sea-floor within the Pacific has not been obscured by sedimentation, we seem justified in concluding that its more notable features—its coastal and central deeps—are characteristic of a subsiding ocean basin. If such be true, then it is not improbable that similar features, obscured by sedimentation, may exist within the Atlantic basin, although, with the exceptions already mentioned, the only deeps now recognisable are those of the central region. The exceptions, however, are very suggestive, occurring as they do in a marginal tract where sedimentation must be at a minimum.

The results of this discussion may now be briefly summed up as follows:—The latest uplifts on the borders of the Pacific bear witness to the close of a prolonged period of crustal compression, which was succeeded, as in many similar but less important cases, by a movement of subsidence that appears to have affected the whole of the intermediate basin.

It was during this movement—a movement probably still in progress—that the remarkable deeps of the great ocean (in which most of the notable earthquakes of the Pacific area seem to originate), and the multitudinous volcanoes of the sea-floor and coastal mountain ranges came into existence.

But the phenomena of the Pacific area have a still wider bearing. More especially would they seem to throw light on the process of mountain-formation, and to negative certain theoretical views to which reference has been made in the preceding chapter. In the first place they support the conclusion that the line along which continental plateau and oceanic basin meet is a zone of special instability. Mountain uplifts and marginal troughs, therefore, tend to be developed in that zone. The facts further demonstrate that such marginal depressions, whether they be due to faulting or to crustal folding, or to both combined, do not owe their origin to sagging of the crust under the weight of accumulating sediments. Again, they show that marginal depressions of the kind—call them geosynclinal troughs if you will—are not necessarily developed everywhere throughout the marginal tracts of a subsiding ocean basin. They are necessarily most conspicuous in regions where sedimentation is relatively insignificant, but are unknown in regions where the very reverse is the case. This is not improbably the reason, as we have suggested, why they are apparently almost entirely wanting in the Atlantic. But whether this be so or not, it is quite certain that the accumulation of

sediment over the marginal areas of the oceanic basin is very unequal. In the Pacific generally, it is insignificant as compared with that taking place in the Atlantic. We seem to understand, therefore, why in some mountain uplifts we should encounter enormous successions of strata belonging, it may be, to only one or two geological systems, while in other uplifts several systems may be represented by a very moderate thickness of materials. In the one case buckling-up has occurred within a region of maximum sedimentation — possibly a geosynclinal depression or extensive marginal trough. In the other case accumulation has been at a minimum, and under such conditions the pavement of older rocks underlying the younger systems may be extensively deformed, and enter largely into the framework of the mountains.

CHAPTER XII

SUBSEQUENT OR RELICT MOUNTAINS

Distinction between denuded Folded Mountains and Subsequent or Relict Mountains. Plateaus of Accumulation and Relict Mountains derived from these. Examples: Torridon Mountains; Heights of Saxon Switzerland; Mountains of Desert Tracts of North Africa, and Bad Lands of Western North America; Basalt Plateaus of the Inner Hebrides, Faröe Islands, etc. Erosion Plateaus and Mountains carved out of these.

SUBSEQUENT or relict mountains differ fundamentally from tectonic or original mountains. They have not been built up after the fashion of volcanoes, for example, neither do they owe their existence directly to deformation of the crust. On the contrary, their most characteristic representatives are remnants of formerly more or less extensive high grounds or plateaus of one kind or another. The strata with which they were once continuous have been gradually reduced and removed by epigene action. Relict mountains are thus monuments of erosion; they have been carved out of rock-masses, the geological structure of which varies indefinitely, but rarely coincides with the outline of the ground. Nevertheless, as we shall learn, the forms assumed by relict mountains are in large measure determined by the

structure and arrangement of the rocks. In our account of tectonic mountains it was necessary to point out that all without exception have been more or less modified by denudation. Such modification in the case of the younger elevations is sometimes inconsiderable; it is quite otherwise, however, with the more ancient tectonic mountains, the original configuration of which has often been completely transformed. Contrast, for example, the appearance of a volcano in vigorous activity with that of one which has long been extinct. Of the latter the only relic remaining may be the plug of rock in the old pipe or funnel of eruption, every trace of a cone having vanished. So again when one compares young folded mountains with similar uplifts of much greater age, one cannot fail to note certain marked contrasts. Amongst recent chains and ranges, for instance, external form and geological structure may to some extent coincide, as in the Jura and the Limestone Alps of Säntis. But such congruity of form and structure rarely or never characterises the more ancient mountains; indeed, even among the youngest uplifts, agreement of the kind is by no means conspicuous. Everywhere these young mountains have been much denuded, and this is true more especially of those that attain a considerable height. In their case the havoc wrought by epigene action has obviously been so excessive — their geological structure or architecture has been so mutilated and ruined, that the work of demolition seems hardly less astonishing than the folding and uplifting of the

mountains themselves. But, notwithstanding all the waste these mountains may have experienced, they must still be included in the tectonic class. Not until they have passed through a cycle of erosion, and been reduced to their base-level or submerged and buried under new deposits, will they cease to be deformation mountains.

When a cycle of erosion is completed, mountains are replaced by a gently undulating plain—a *plain of erosion.* Many such are known, and that they occupy the sites of vanished mountain chains is clearly indicated by their internal or geological structure. Some of these old plains of erosion, like that of the Belgian coal-fields, reach no great height above the sea, while others attain considerable elevations, forming lofty plateaus. A study of such plateaus shows us that a chain of original or tectonic mountains, after it has experienced much denudation—after it has been reduced to its base-level and replaced by a plain of erosion—may again be uplifted without undergoing renewed folding. The crust may once more bulge up, and the *plain* be gradually carried to such a height that it then becomes a *plateau of erosion.* Or, instead of being thus elevated, the plain may become submerged for a longer or shorter period of time. During protracted subsidence sediment may gather over the surface of the drowned land to such an extent that the site of the former mountain chain may eventually be buried under a thickness of many thousand feet of stratified materials—gravel, sand, mud, etc. Subsequently the movement of depression

may cease, and be replaced by movement in the opposite direction—a general bulging-up or elevation of the area may take place. Should such ensue, then the buried plain of erosion will again rise out of the sea, and may even attain a height of many thousand feet above that level. In that case we should speak of the newly formed plateau as a *plateau of accumulation.* A section across it would show that the upper portion of the elevated area consisted of a great thickness of approximately

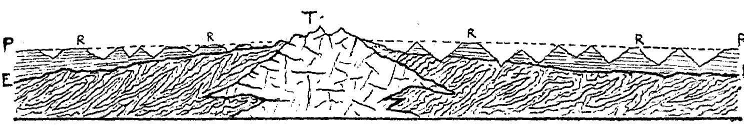


FIG. 48.—Diagrammatic Section of Plateau of Accumulation superposed on Plain of Erosion.

E-E, Plain of Erosion, replacing Chain of Folded Mountains; T, Torso Mountains—the Worn Stumps of the Former Mountain Chain; P P, Plateau of Accumulation—Horizontal Strata out of which Relict Mountains (R, R) have been carved.

horizontal strata resting upon and concealing the old plain of erosion (Fig. 48).

Although tectonic mountains tend to be gradually ground down to their base-level, it is seldom that the cycle of erosion is completed. Long before the mountains have entirely vanished, renewed crustal deformation may take place, and the much denuded area be either re-elevated or submerged, according as the earth-movement is up or down. In the former case we get a plateau of erosion, the surface of which may be more or less irregular—ribbed and knotted with the straggling cores and stumps or torsos of the

ancient mountains. In the latter case, the sorely denuded mountain-land, carried down below sea-level, becomes in time covered with sediments, underneath which the lower lying parts of the plain of erosion may eventually become deeply buried. Should the stumps or torsos of the old mountains remain above sea-level as islets, they will of course escape burial, only to be subject, however, to continuous erosion. But should they be submerged, then they also will in time become partially or entirely concealed under gradually accumulating sediments. At a later period, should the sunken area be re-elevated *en masse* to a very considerable height, we shall have a plateau of accumulation, consisting of approximately horizontal strata resting upon the irregular surface of the old plain of erosion. The horizontal strata will naturally attain their greatest thickness upon the lowest lying portions of that plain, and will thin away as they approach the torsos of the mutilated mountains, the summits of which may even peer above the surface of the plateau, as so many islets in a far-stretching sea (Fig. 48).

Examples of all these several stages and conditions are met with again and again, but it is not necessary for our purpose to go into detail. For the present it is sufficient to realise the fact that plateaus are of two kinds, namely, *plateaus of accumulation*, and *plateaus of erosion*. The former consist, for the most part, of horizontal or gently-inclined strata, often resting upon and partially or wholly concealing an ancient plain of erosion. The latter are built up almost invariably of

highly-inclined and disturbed rocks. In the case of the former, therefore, the shape of the ground is determined by the arrangement of the strata: in the case of the latter there is usually no coincidence between external form and internal structure.

Relict Mountains carved out of Accumulation Plateaus.—Now it need hardly be said that plateaus, like all other land-forms, are in time modified by erosion. Just as tectonic mountains of every type pass through a cycle of denudation, which may or may not be interrupted by earth-movements, so a plateau becomes in like manner the prey of the

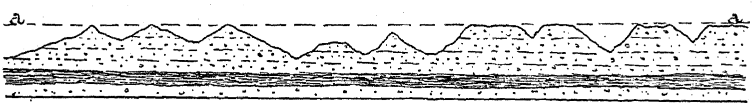


FIG. 49.—Relict Mountains carved out of a Plateau of Accumulation. *a*, *a*, Original Surface of Plateau.

epigene agents, and may eventually be reduced to its base-level. After a plateau has been deeply incised by streams and rivers, when it has become traversed by a whole network of valleys, it gradually loses the appearance of a table-land, and assumes that of a truly mountainous region. This transformation is wholly the result of denudation. The mountains and hills are not original or tectonic, but *subsequent* or *relict*. They have not been constructed or built as mountains, but are merely remaining portions or fragments of a formerly more extensive elevated area. They have been carved out of an old table-land, and shaped into mountains by the gradual removal of

masses by which they were at one time surrounded (Fig. 49).

The form assumed by relict mountains depends mainly upon the nature and arrangement of the materials out of which they have been carved. A plateau of accumulation, for example, tends to be cut up into a series of pyramidal or tabular mountains, and crested or flat-topped ridges, separating the various valleys from each other. And as the latter are deepened and widened, the massive segments of the old plateau become progressively narrower and gradually reduced in height. At a later stage most of these mountainous segments may have disappeared, and only a few isolated cones and ridges or truncated pyramids may be left. Finally, every height may be levelled, and the old plateau be replaced by a plain of erosion.

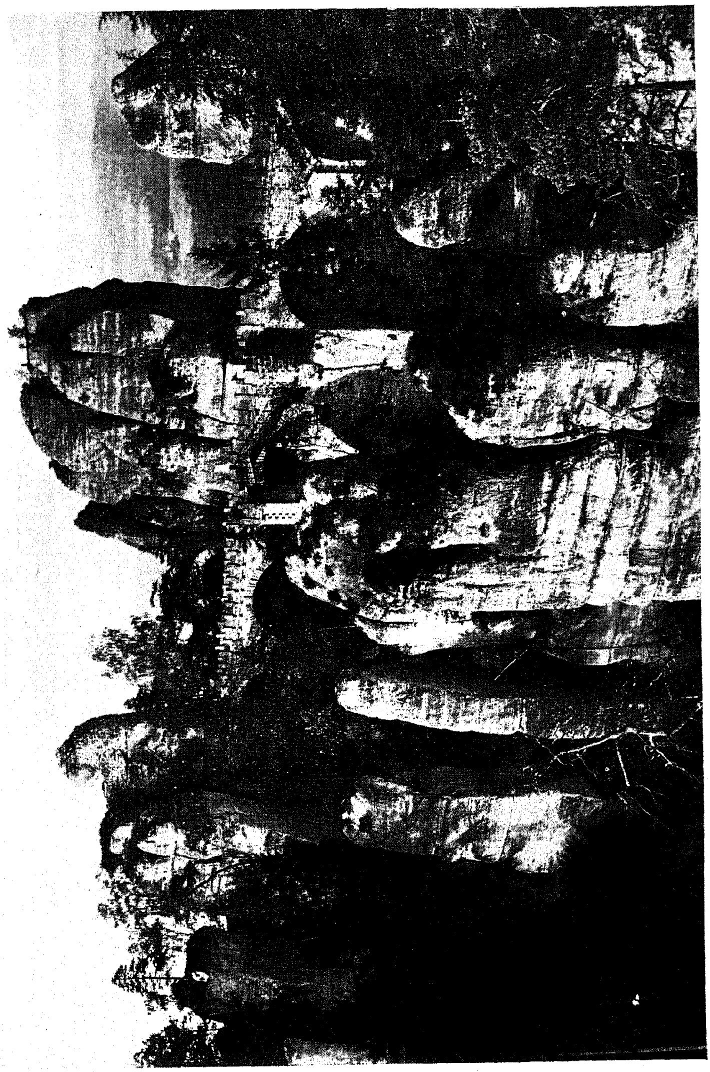
It must be noted, however, that in the denudation of a plateau of accumulation the character of the climate usually plays an important rôle. In a region which is practically rainless, for instance, rivers tend to cut out steep-sided or **U**-shaped ravines and cañons. But under conditions of rainfall similar to those of our own and other temperate lands the valleys assume a different form, their cross-section being usually **V**-shaped. The reasons for such differences are obvious. In a well-watered region rain passes down through the rocks and comes out on valley-slopes as springs which tend to undermine the rocks above their outlets, so as to cause collapse of less or greater extent, a process often intensified by frost. In rainless

tracts, however, the valleys are deepened and widened by the vertical and under-cutting action of the rivers alone. Any modification of the walls of the valleys is the result either of disintegration brought about by the expansion and contraction of the rocks, due to extremes of heat and cold, or to the erosive action of the wind, or to both causes combined. But while the forms of the valleys and the configuration of the mountains are influenced by climatic conditions, they are, nevertheless, primarily determined by the character of the rocks and the geological structure.

Truncated pyramids and pyramidal mountains, then, may be considered the typical forms carved out of plateaus of accumulation. Under favourable conditions, mountains of this kind often ascend in a series of abrupt terraces, or corbel steps. But much depends on the nature of the rocks. If the strata be more or less homogeneous in character, the step-like outlines are not likely to be pronounced. Instead of abrupt pyramidal heights we may have smooth rounded hills. The character of the climate has also a powerful influence, an arid climate fostering the formation of more or less abrupt pyramidal mountains; while under moist conditions the configuration of the heights tends to be smoother and less abrupt. Nevertheless, whether the horizontally bedded rocks be of one kind or another, or show alternations of many different kinds, and whether the climate be dry or humid, equable or the reverse, tropical, temperate, or arctic, the mountains and

hills carved out by the action of the epigene agents are of the same type.

The picturesque heights of Saxon Switzerland have been hewn out of Mesozoic sandstones, arranged in approximately horizontal beds (Plate LX). The dominant rock of the region is a much jointed, fine-grained sandstone, having a maximum thickness of more than 1000 feet. In many places it shows the smoothly rounded grains and the diagonal bedding so characteristic of wind-blown formations, and the rock may thus, in part at least, represent the dunes that gathered along the margin of the Cretaceous sea of central Europe. It is characterised especially by its two sets of vertical joints, which cut each other and the planes of bedding at approximately right angles. The sandstone thus tends to break up into cuboidal or quadrangular blocks, whence it gets its name "Quadersandstein." Being porous and much jointed, it is easily disrupted by epigene agents. From wide tracts it has largely disappeared, the remnants assuming the form of steep-walled, flat-topped, and sometimes broken hills, which from a distance look not unlike ruined mediæval castles and fortresses. In many places the rock has been carved and worn into labyrinths of fantastic towers and steeples, pillars, and irregular upstanding masses, pitted and drilled by cave-like hollows, or pierced through from side to side so as to form picturesque arches. The general aspect of the region and the bizarre shapes of the ruinous rock-masses, recall the appearances presented by those of desiccated



THE BASTEIBRÜCKE, SAXON SWITZERLAND. [Horizontally bedded and vertically jointed sandstone.]

Photo, Photochrom Co.

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desert lands, where the peculiar features are due chiefly to the action of wind. Some geologists, therefore, are inclined to infer that the salient features of Saxon Switzerland may have been acquired under different climatic conditions from the present. They remind us that during a certain stage of the Ice age central Europe was a wind-swept tract of steppes and deserts, and that the Quadersandstein could hardly fail to have been influenced at that time by wind erosion. However that may be, it is certain that under existing conditions the picturesque aspect of the land is not likely to be soon remodelled, for after all it is the peculiar character of the rocks which has determined the results worked out by erosion. Under the influence of frost and thaw the sandstone crumbles away and its joint-faces are wedged asunder, while plants take a not unimportant share in the work of destruction. In rainy weather the result of this joint-action is seen in the quantities of sand swept down to the Elbe by numerous brooks and streams.

We may now briefly consider the forms assumed by horizontal strata in dry desert regions, where the work of rain and frost is practically negligible. In those regions changes of temperature are among the most potent causes of rock-disintegration and disruption. Changes of the kind are, of course, experienced everywhere, but their effect is necessarily most notable in places where the diurnal range of temperature is great, as in the drier tracts of tropical and subtropical latitudes. In such regions bare rocks may be warmed

up during the day to 140° F. or more; but, since rocks are bad conductors, it is only their superficial portions that can be so highly heated. These expand, and in so doing become detached from the cooler rock underneath, and bulge upwards. All masses exposed to powerful sun-heat have in this way a tendency to exfoliate. At night so great is the radiation, especially when the sky is clear, that the temperature at the ground often falls below the freezing-point. The expanded rock-surfaces under such conditions rapidly contract, and are thus shattered and reduced to fragments. So effectual is insolation, that were no other agent of denudation involved in the reduction of the rocks of a warm desert region, these would eventually become buried under their own ruins, and thus be protected from further waste of the same kind.

The disintegrated rock-material, however, is not allowed to accumulate to an indefinite extent. Torrential rain during occasional thunderstorms serves to wash it away. But a much more important co-worker with insolation is wind, which shifts and sifts the loose material, and eventually carries it off, so as to leave fresh surfaces exposed to the process of alternate heating and cooling. Further, the grit, sand, and dust blown about by the wind play the part of a sand-blast, abrading and eroding the rocks against which they are driven. Insolation and "deflation" (as the transporting action of the wind is called) thus work together, with the general result that the whole

surface of a warm rainless tract tends to be gradually lowered.

Although insolation and deflation operate in a very different way from rain, frost, and running water, their work nevertheless is determined, guided, and controlled, as it were, by the nature and structure of the rocks they attack. A dry desert plateau of accumulation tends to become dissected, and eventually resolved into tabular and pyramidal hills and mountains. In the Sahara many excellent examples have been observed. The rocky plateaus of that region are often traversed by dry winding gullies, ravines, valleys, and other abandoned water courses, showing that what are now desert tracts have in former times experienced a relatively humid climate. The wind sweeping through the depressions in question has attacked the exposed outcrops of the strata, eaten out innumerable cirque-shaped hollows in the steep walls of valleys, and so modified the features due to the former action of rain and rivers, that some observers have thought it probable that all the hollows and depressions of the land may be the result of wind erosion alone. In many cases, indeed, as Professor Walther has shown, stream and river action must be excluded, the features of the land being solely due to sun and wind. Steep-walled wâdis, terminating in cirque-heads, have been ground out by sand-laden wind, and are being steadily driven from all directions into the heart of a plateau, which is thus becoming cut up, as it were, into irregular segments, forming tabular or conical and pyramidal

heights (Fig. 50). When the constituent rocks are of homogeneous consistency, they assume the form of conical or rounded hills and ridges; but when relatively hard beds are intercalated among them, the hills become tabular or pyramidal, and are often barred horizontally by one or more projecting ledges. These ledges, it need hardly be said, are the outcrops of the relatively harder rocks. But while the general configuration of the heights quite recalls that of the hills and mountains carved out of accumulation-plateaus in well-watered regions, yet the subordinate features and detailed sculpturing of the rocks are more particularly characteristic of wind erosion. The niches and amphi-

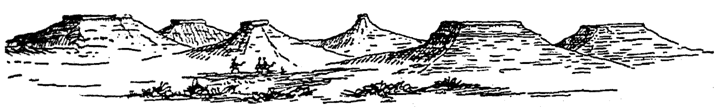


FIG. 50.—Wind Erosion: Tabular and Pyramidal Heights of the Sahara. (Mission de Chadamès.)

theatres of all dimensions which indent the walls of the broad wâdis, and the manner in which the rock-surfaces are everywhere fretted, honeycombed, and drilled, are peculiar to arid regions where wind is the dominant agent of destruction.

In certain semi-desert regions the destructive action of insolation and deflation, although it may be notable enough, is not infrequently surpassed by that of torrential rain. The phenomena are well displayed in the great plains that sweep out eastwards from the foot of the Rocky Mountains, as in some parts of the Dakotas, Nebraska, Wyoming, Colorado, etc. The precipitation in the regions referred to is really great,

but often very unequally distributed over the year, coming in heavy showers after long intervals of drought, during which the land is swept by severe hot winds. In many places, therefore, arid conditions prevail and vegetation is practically absent. The plains are plains of accumulation, consisting of a great succession of horizontally or very gently-inclined beds of slightly consolidated sandstones, loose sands, and soft clays, and loams of Cainozoic age. Having no vegetable covering to protect them, these strata have suffered much erosion. The clays naturally succumb most rapidly to the action of heavy rains, but even the soft sandstones readily yield. Owing to the unequal consistency of the latter, however, they often tend to assume peculiar and fantastic forms. In Plate LXI, the effects produced by rain are well shown by the trenched and furrowed aspect of the clay-heights in the background. The hummocky surface of the sandstone in the foreground is doubtless in large measure due to the same action, but insolation and deflation have in all probability shared in the work.

The result of the combined activities of rain and sun and wind on these elevated plains of the "Far West" has been the reduction of the general level of the land, and the formation during the process of tabular, pyramidal, and rounded heights and ridges in bewildering variety. In some parts of these "bad lands," as the arid tracts are called, the hills are not so closely crowded together, the broad plains being diversified only here and there with straggling heights

or an occasional butte or mesa, or, it may be, by merely a few isolated columns and pillars. The buttes and mesas are the most characteristic types, both rising somewhat abruptly, the former as steep-sided bastions (see Plates LXII, LXIII, LXIV) and towers, or in heavier, more extensive masses, not infrequently peaked but sometimes rounded and dome-shaped. Mesas, on the other hand, owing to the presence of a relatively hard coping, are usually flat-topped or tabular. As both types are developed in horizontal strata, the more resistant beds project on the flanks of the hills as prominent ledges; in short, the heights are apt to present the corbel-stepped features so characteristic everywhere of hills having the same geological structure. Nowhere, perhaps, can the development of buttes and mesas be more satisfactorily studied than in the cañon region of Colorado, a peep into which is shown in Plate LXV.

The examples now adduced may suffice as illustrations of the forms assumed by the remnants of a plateau built up of horizontally arranged sedimentary strata. Many well-known accumulation plateaus, however, consist wholly or at least very largely of igneous rocks, and it is necessary to consider how these become broken up, and to note what types of hill and mountain are evolved during the process. We have not far to go in search of examples, for denuded plateaus of the kind are well represented in our own islands. Many of the Inner Hebrides are the sorely reduced fragments of what was at one time an extensive igneous plateau, a plateau which

included not only some portions of the Scottish mainland but the northern part of Ireland. How large an area that old plateau may formerly have occupied can only be conjectured, but it not improbably stretched far away in the direction of the Faröe Islands, with which, indeed, it may well have been continuous. It is apparent at all events that the basalt-rocks of the Inner Hebrides and Antrim are mere wrecks of a great plateau of accumulation, for everywhere its remnants consist of approximately horizontal lavas with their accompanying tuffs. To trace the history of the plateau in question is beyond our purpose, all that we are at present concerned with being the forms of the hills and mountains carved out of it. These, as might have been expected, are of the usual types assumed by horizontally disposed strata undergoing denudation—tabular and pyramidal. But inasmuch as the lavas are considerably more resistant than their accompanying tuffs, they tend to project as more or less pronounced ledges, so that seen in profile the hills and mountains are corbel-stepped (see Plate LXVI). It is this well-marked feature that suggested the term "trap-rocks"[1] formerly applied to the old basalts of this and other countries. When the soft tuffs occur in thin layers the basalt-steps are narrow, rising rapidly one above another, and the mountain-slope is often somewhat abrupt or even precipitous. But with relatively thick tuffs, the steps broaden out and the mountain profile tends to be less steep. Frequently the angular outlines are softened

[1] *Trappa* (Swedish), stairs or steps.

by the action of frost and rain, the steps becoming more or less obscured, but seldom being quite obliterated by the accumulation of rock-riven debris or rubble. In pre-glacial times these corbel-steps must have been generally sharper than they are at present, glacial action having subsequently bevelled their edges and reduced the asperities of the mountain slopes. Under existing conditions, however, the more pronounced pre-glacial features are gradually being reproduced.

The phenomena of the trappean hills and mountains of the Inner Hebrides are repeated in the lonely group of the Faröe Islands, similarly built up of basalt, with thin intervening layers of tuff, arranged in approximately horizontal strata (Fig. 51). "These islands," as we have elsewhere said, "are for the most part high and steep, many being mere mountain ridges that sink abruptly on one or both sides into the sea. The larger ones show more diversity of surface, but possess very little level land. All have a mountainous character, and, owing to the similarity of the rocks and their arrangement, exhibit slight variety of feature. They form as a rule straggling, irregular,

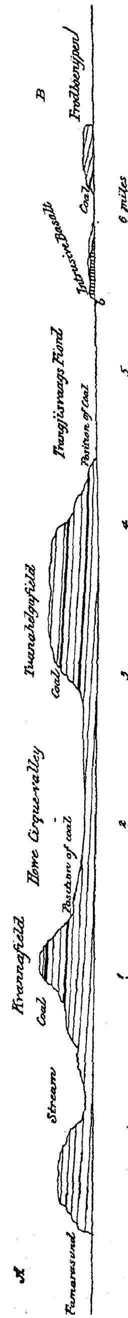
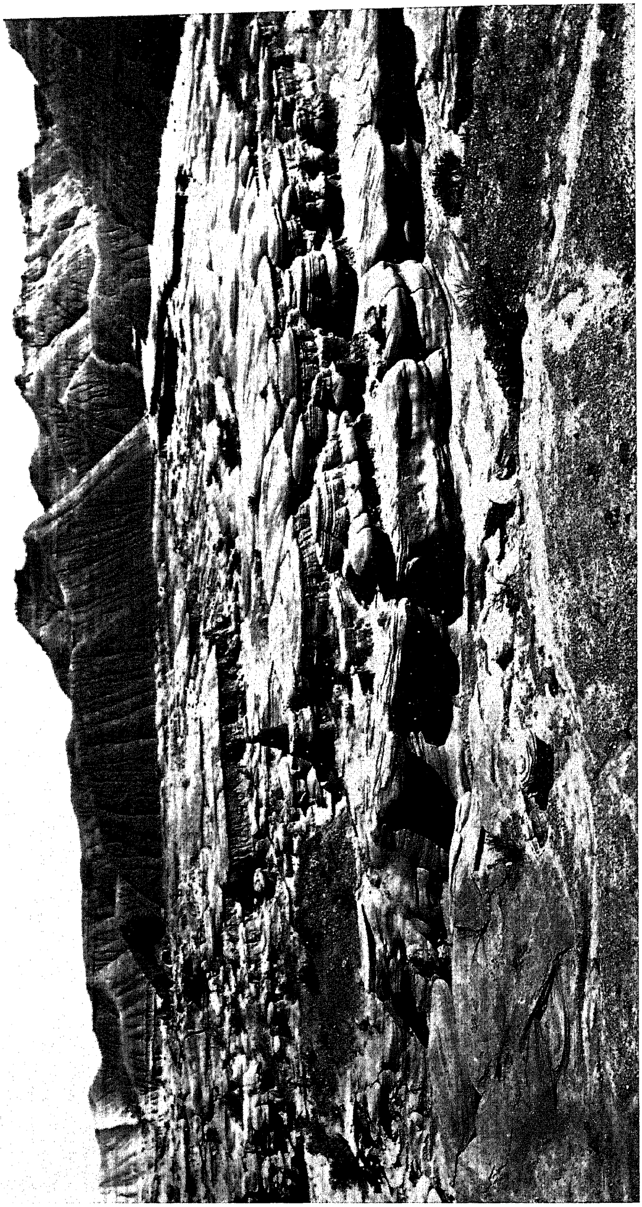


FIG. 51.—Section across Suderröe, Faröe Islands. The island is composed chiefly of beds of basalt, with associated thin tuffs.

PLATE LXI.



TOADSTOOL PARK, IN BAD LANDS, NORTH-WEST OF ADELIA, NEBRASKA.

Photo, U.S. Geological Survey: Prof. Paper 17, 1903.

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flat-topped masses, and sharper ridges that are notched or broken here and there into a series of isolated peaks and truncated pyramids. Sometimes the mountains rise in gentle acclivities, but more generally they show steep and abrupt slopes, which in several instances have inclinations of 25° to 27° or even 30°. In many places they are even steeper, their upper portions especially becoming quite precipitous. They everywhere exhibit a well-marked terraced character, cliffs or long bare walls of rock rising one above another, like the tiers of some cyclopean masonry, separated by narrow intervening slopes, sparsely clothed with grass and moss, or sprinkled with fallen rock-rubbish. The coasts are usually precipitous, many of the islands having only a few places where a landing can be made."

Similar highly denuded basalt plateaus occur in many other regions, such as that of the Deccan in India, which occupies an area of some 200,000 square miles; but the samples already given may suffice.

Hitherto we have been considering accumulation plateaus as if they consisted exclusively of horizontal or approximately horizontal strata. But such is not always or even often the case. One and the same plateau may show horizontal beds in one part, inclined and undulating strata elsewhere. Not infrequently the surface of an accumulation plateau may be gently inclined for a long distance in one direction, this inclination coinciding, it may be, with the dip of the strata. Or the surface may now and

again be diversified with parallel banks or ridges and troughs or hollows corresponding to similar folds of the constituent strata. An accumulation plateau of inclined strata, after long exposure to epigene action, must obviously become cut up into segments of various dimensions. But these remnants will differ in certain notable respects from the segments carved out of horizontal strata. The primeval rivers of a plateau of inclined strata will naturally follow the direction of the dip; but as the drainage system becomes more and more developed, the main river or

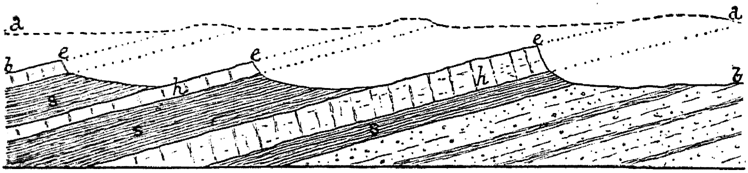
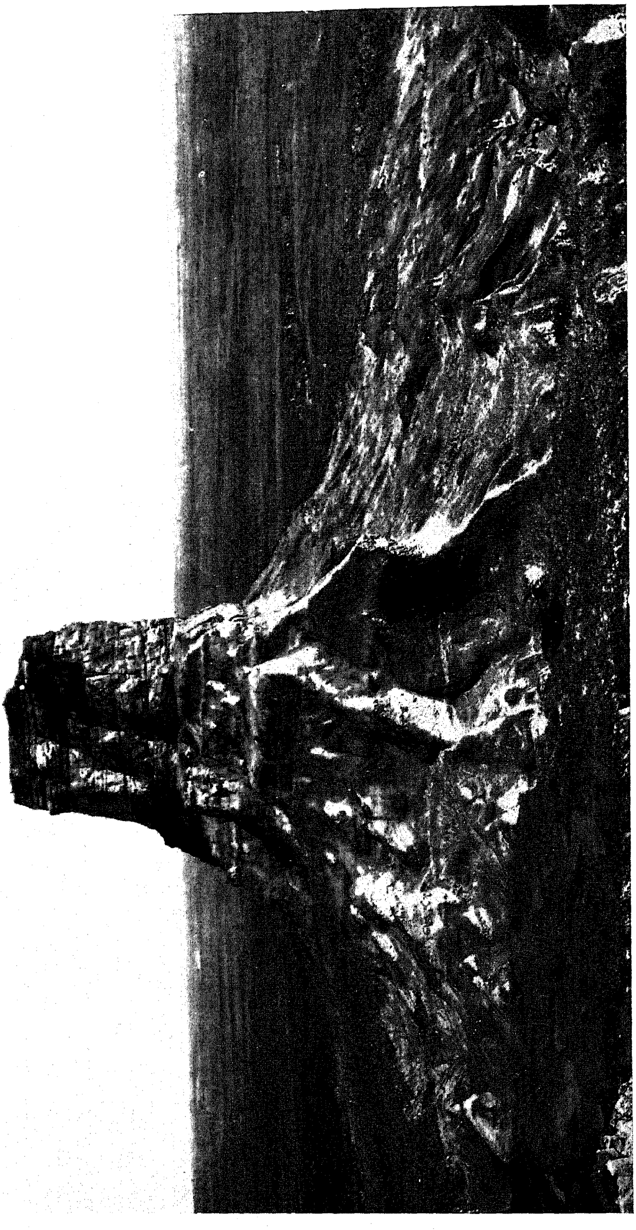


FIG. 52.—Relict Hills carved out of Inclined Strata.

a, a, Earlier Surface of Plateau; *b, b*, Present Surface of the Ground; *e, e*, Escarpments and Dip-slopes; *h, h*, Relatively "Hard" Rocks; *s, s*, Relatively "Soft" Rocks.

rivers will by and by be joined by many lateral streams, the courses of which, instead of coinciding with the dip, will usually traverse it at various angles. In a great succession of strata some of the rocks are almost certain to be more durable than others (see Fig. 52). When the surface of the whole region, therefore, has been lowered, and valleys broad and narrow have been well developed, the relatively hard rocks will tend to project above the general level of the denuded land. The outcrops of these will then face in the direction of the watershed, forming more or less pronounced escarpments with dip slopes

PLATE LXII.



JAIL ROCK (A BUTTE), FROM THE WEST; BAD LANDS, NEBRASKA, U.S.A.

Photo, U.S. Geological Survey: Prof. Paper 17, 1903.

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behind. Such, in a few words, is the origin of the leading hill-features of central England. The general inclination of the strata from near the Welsh borders to the shores of the North Sea is easterly at a low angle, so that in traversing the country in the line of dip we cross the outcrops of several great geological systems. The strata vary considerably in character, some being relatively soft, such as clay and shale, and others relatively hard and usually more porous, such as limestone, chalk, etc. As might have been expected the outcrops of the latter project more or less prominently, forming long lines of escarpment

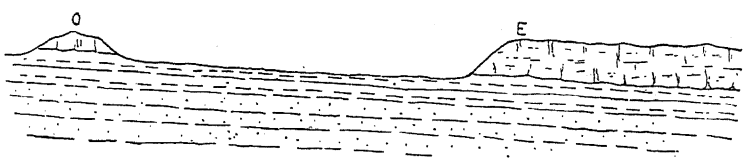


FIG. 53.—Broad Belt of High Ground with Escarpment E, and Outlier of same O.

hills which face the west, and trend in a general northerly or north-easterly direction.

It is obvious that the width and relative height of an escarpment hill will be determined by various factors. Other things being equal, the hilly ground will be broad or narrow according as the dip of the strata is low or high. With a low dip a relatively inconsiderable thickness of hard rock may give rise to a broad belt of high ground (Fig. 53), while with a somewhat steep dip the same thickness of rock may be represented by merely a narrow ridge (Fig. 54, p. 264). Again, should the hard strata be several hundred

feet thick, the escarpment formed by them will usually attain a greater height than would have been the case had the hard rocks been much thinner. Once more the height of an escarpment will often largely depend upon the relative durability of its rock-constituents, as compared with that of the more yielding strata above which it rises. If the disparity be great the escarpment will, as a rule, be much more prominent than would have been the case had the

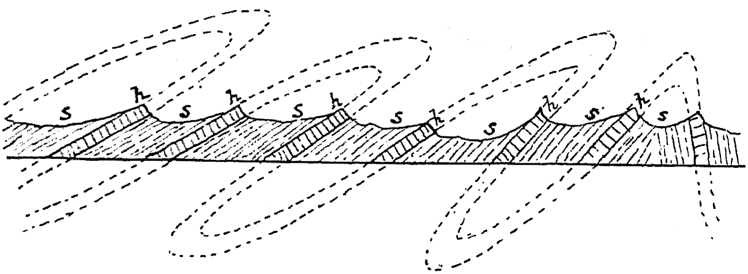
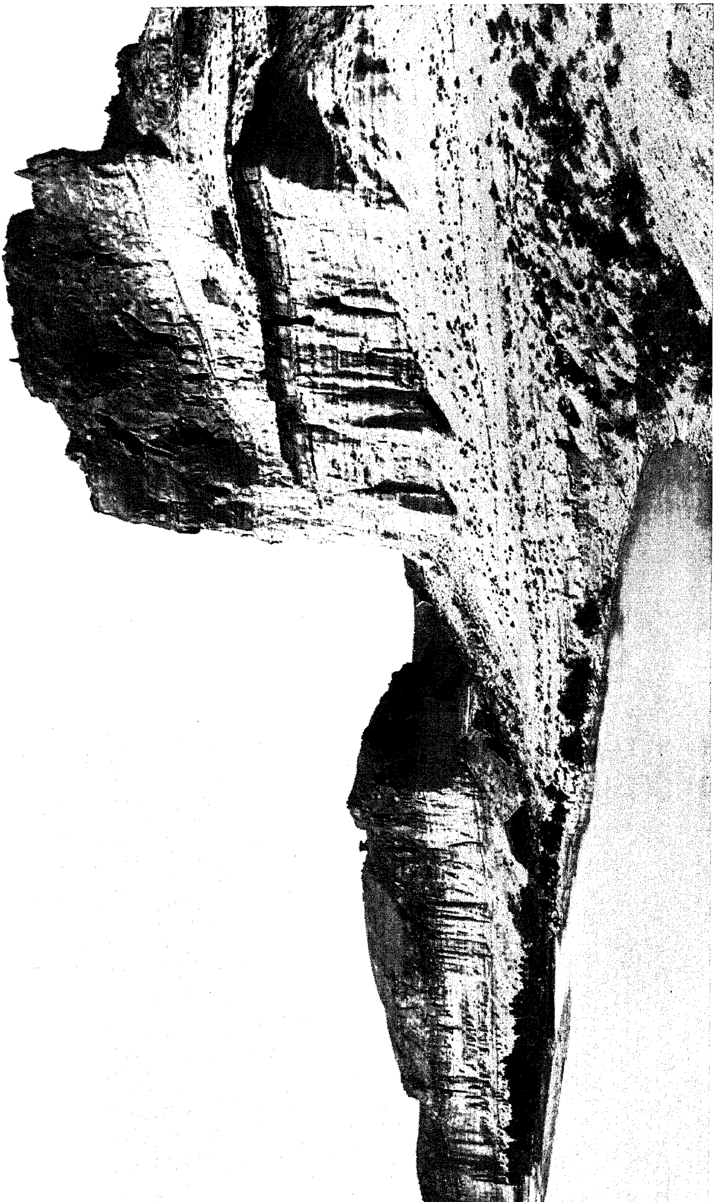


FIG. 54.—Steeply-inclined Strata giving rise to Narrow Escarpments and Ridges.

difference between the two sets of rocks been less pronounced.

As true escarpments owe their existence to the presence of relatively hard rocks interstratified in a series of more yielding strata all inclined in one direction, it is necessarily the type of hill characteristic of countries which show the same geological structure as central England. In regions of undulating strata the hill-forms are frequently more varied; much, however, depends upon the character of the strata. Should these consist of a monotonous succession of rocks, differing little as regards durability,

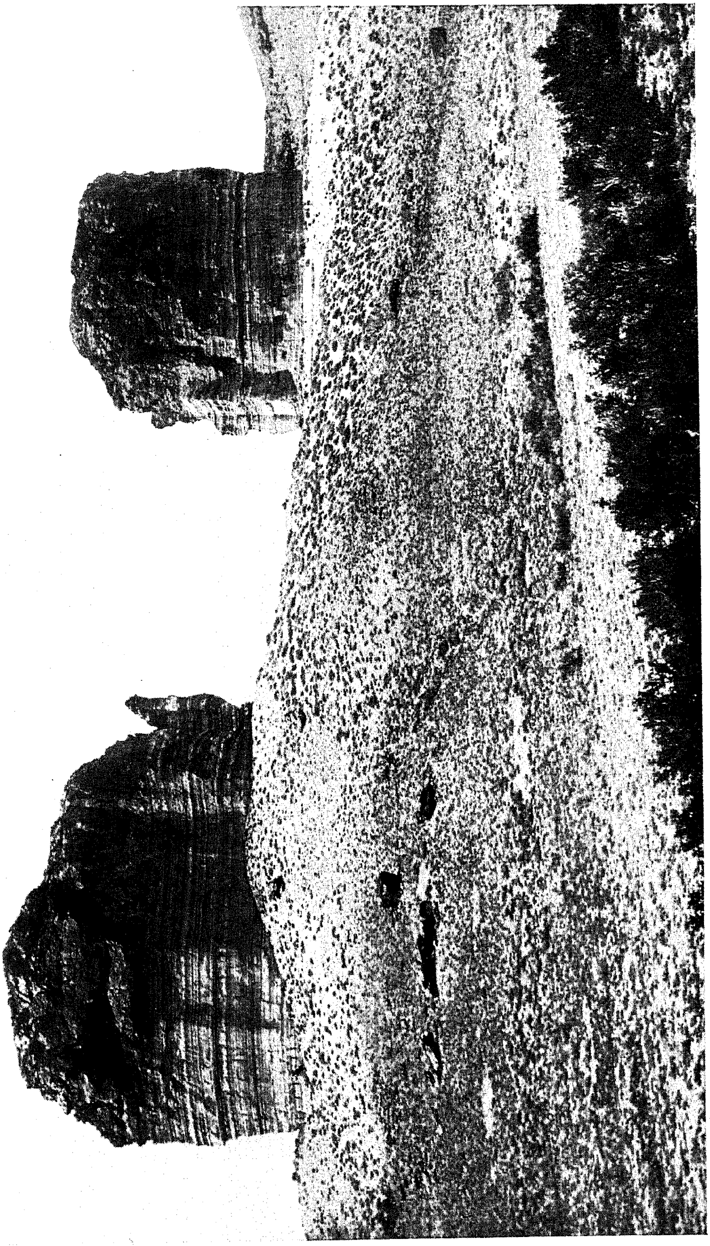
PLATE LXIII.



SANDSTONE BUTTES, GREEN RIVER, WYOMING, U.S.A.

Photo, Photochrom Co.

PLATE LXIV.



"GIANT CLUB AND KETTLE," SANDSTONE BUTTES, GREEN RIVER, WYOMING, U.S.A.
Photo, Photochrom Co.

[*Between pages* 264 *and* 265.

no strongly contrasted features are likely to be developed. But, wherever marked disparity occurs, it is certain to influence the configuration of the ground. This is often conspicuously displayed in tracts where the strata are arranged in more or less pronounced anticlines and synclines. Synclines

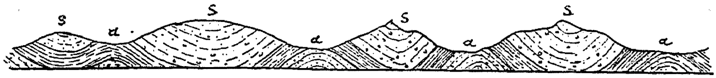


FIG. 55.—Appalachian Ridges of Pennsylvania.

being the more resistant structures tend to be sculptured into hills, while anticlines, on the other hand, are apt to be replaced by hollows (see Fig. 55). In many cases, however, when an anticline consists of a series of strata, some of which are yielding while others are more durable, they have frequently been carved into a double set of

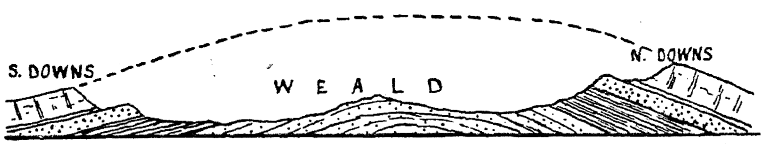
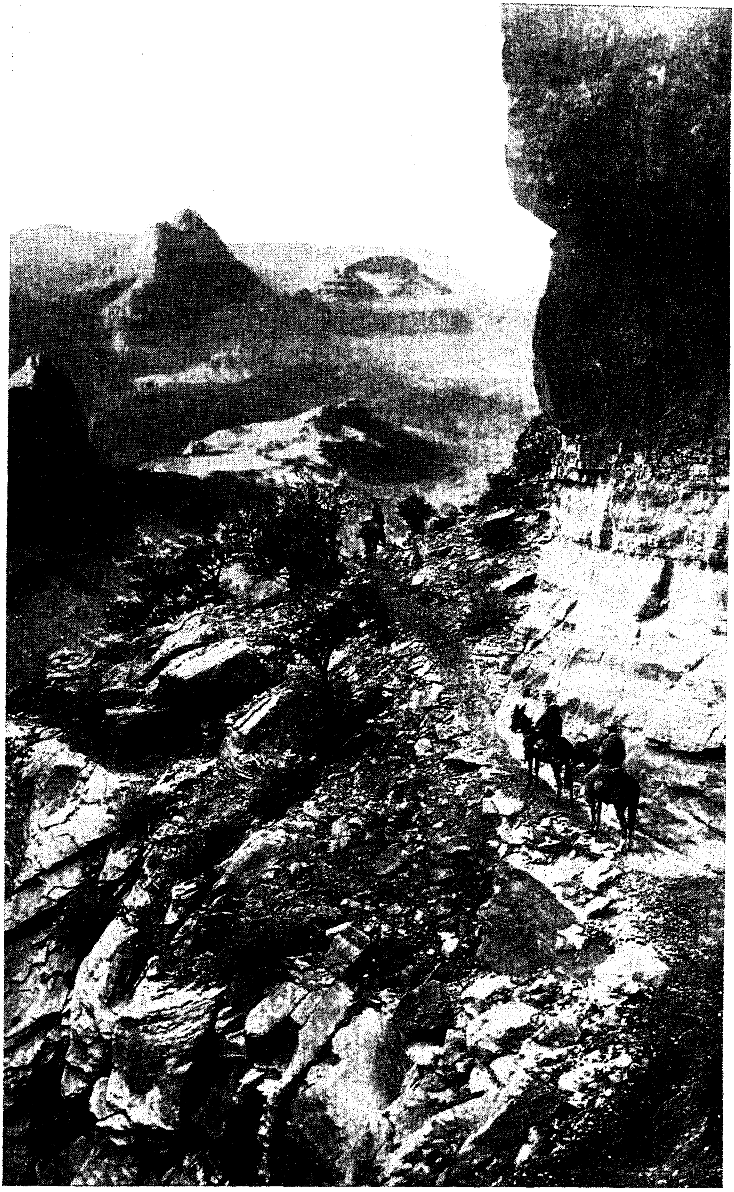


FIG. 56.—Section across the Weald—a Denuded Anticline.

escarpment hills facing each other, as in the well-known example of the Weald (see Fig. 56). But the influence of geological structure in determining the features developed by erosion and denudation has already been indicated more or less fully in preceding chapters, and need not be further discussed. In the present chapter we have been considering the more notable types of mountains and hills character-

istic of highly denuded accumulation plateaus, and we may now conclude with a few notes on the several types of relict mountains derived from the dissection of erosion plateaus.

Relict Mountains carved out of Erosion Plateaus. —We had occasion to refer in an earlier chapter (see p. 170) to that very ancient chain of tectonic mountains known to geologists as the Caledonides. It is needless to say that mountains so old must have experienced many changes. Into the history of these changes it is impossible to enter; indeed much of that history is as yet only dimly understood, and it must suffice, therefore, for our purpose to sketch as shortly as may be the general outcome of the revolutions referred to. Briefly, then, we may note that the mountains during the Palæozoic era were subjected to powerful denudation, so that long before the close of that era they had already been largely reduced. Even before Old Red Sandstone times very considerable areas of the mountain-land had been levelled. At the beginning of that period, therefore, when a slow movement of depression supervened, wide tracts of the levelled land sank in the waters of inland seas or great estuaries. But throughout the Old Red Sandstone period, much of the Highland area retained a mountainous character. The period was one of marked subterranean activity, many volcanoes erupting upon the floor of the inland seas, while others poured out their lavas on the land. Under continental climatic conditions vast quantities of decayed rock-



HANCE'S TRAIL, GRAND CAÑON OF THE COLORADO, U.S.A.
Photo, Photochrom Co.

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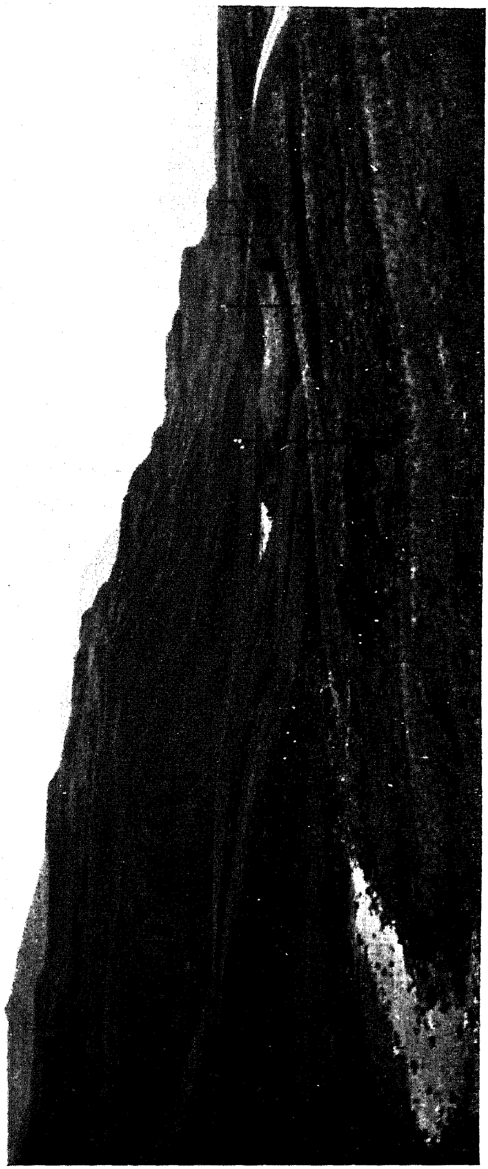
material mantled the mountain slopes and overspread the low grounds, while torrents, streams, and rivers carried down their quotas of detritus to estuary or inland sea.

We know very little of the geological history of the Highlands in later Palæozoic and Mesozoic times. The occurrence of patches of Carboniferous strata at Ardtornish, on the Sound of Mull, and at the north-west end of the Pass of Brander, shows that the area must have been invaded by the Carboniferous sea, but to what extent we do not know. The probabilities are, however, that the submergence was not general, and that dry land persisted within the Highland borders down to the close of the Palæozoic era. Mesozoic strata are likewise met with in certain peripheral tracts from which similar conclusions may be drawn; they undoubtedly indicate considerable submergence in Jurassic and Cretaceous times, but the extent of these marine transgressions is quite uncertain. We have no reason to believe, however, that dry land has ever ceased to exist within the Highland area since Old Red Sandstone times.

Notwithstanding the incompleteness of the stony record, the deficiency is partly supplied by a critical study of the physiographical features of the country. The architecture and general aspect of the land show that the Highlands are the relics of an ancient plateau. During some period, perhaps during more than one period, the region has been levelled. The earliest notable epoch of denudation immediately

preceded the formation of the Old Red Sandstone. The next supervened when the region was re-elevated after Old Red Sandstone times, and the uplifted area then appeared as a plateau, partly of erosion, partly of accumulation. Probably at that period considerable tracts of the old Caledonian Mountains, still unsubdued, rose above the general level of the plateau, and it would seem as if the chief lines of drainage, the more important valleys of the Highlands, may then have been initiated. We must note, however, that in the West Highlands (Morven) patches of Cretaceous strata, preserved under Tertiary lavas, are seen resting directly upon the eroded surface of the Highland schistose rocks at a height of more than 2000 feet above the sea. Undoubtedly these patches with their caps of basalt were formerly continuous, their present isolation being the result of excessive erosion and denudation. Are we to infer from this evidence, therefore, that the uplift of the Highland plateau did not take place until the close of the Mesozoic era, that the excavation of the Highland valleys does not date back beyond Tertiary times? It is hard to believe that such is the case, and yet there is no actual evidence to the contrary. It may be noted, however, that Morven, in which the patches of Cretaceous strata occur, lies on the immediate borders of the Tertiary volcanic region of the Inner Hebrides, and may well have participated in the crustal movements which affected that region. The movements of elevation and depression that have taken place within late



VIEW IN GLEN VARRIGILL, SKYE. [Horizontally bedded Basalt, showing corbel-stepped profiles.]

Photo, J. W. Reoch, Esq.

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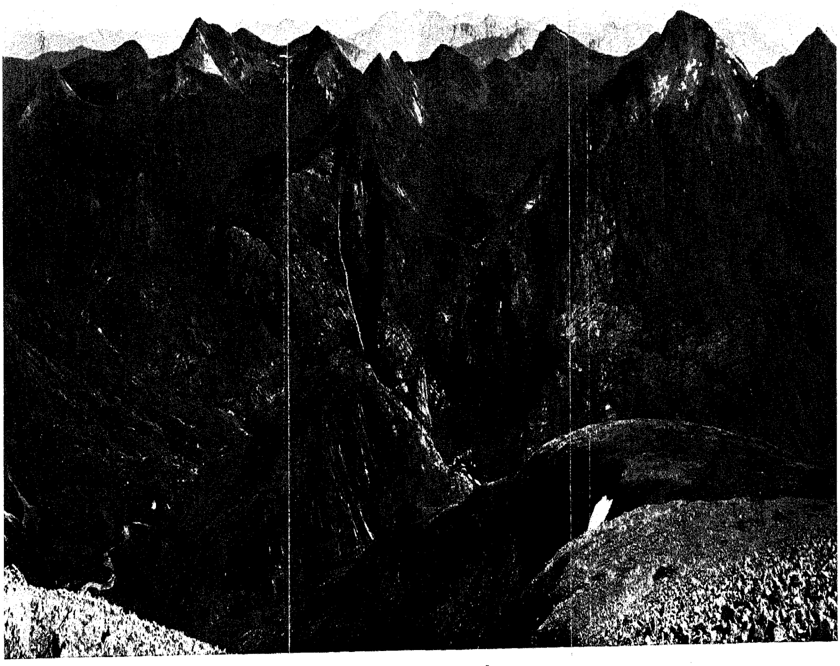
geological times throughout the great volcanic tract extending from the Hebrides to Iceland appear to have been on a much larger scale than is generally understood. To whatsoever extent these movements may or may not have affected the Highland plateau, it must be admitted that certain Highland valleys have certainly been excavated since Tertiary times, and we may well believe that many other valleys throughout the Highlands are of similar recent age. But this admission does not negative the conclusion that the direction of the chief rivers was determined, and the erosion of their valleys initiated at a far earlier period, not improbably as far back as late Palæozoic times. But the history of the Highlands during the protracted Mesozoic and Cainozoic eras is almost a blank. To what extent the land may then have been base-levelled we do not know, and we are equally ignorant of the amount of depression and re-elevation it may have experienced. As already remarked, however, dry land within the Highland area has not improbably persisted since the close of the Old Red Sandstone period. From our present point of view, therefore, all that we need keep in mind is simply this, that the Highland plateau is one of erosion and accumulation. If we picture to ourselves its higher portions as consisting of the much denuded but still dominant torsos of the old Caledonian mountain-land, and the less elevated tracts as being largely occupied by Old Red Sandstone and perhaps younger strata, we shall have a sufficiently accurate impression of



VIEW FROM THE SHOULDER OF BEN NEVIS, LOOKING SOUTH.

Photo, H.M. Geological Survey.

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other. One sees "no great disparity in height amongst the dominant points of individual groups. Take, for instance, the knot of mountains between Loch Maree and Loch Torridon. There we have a cluster of eight mountains, the summits of which do not differ much in elevation. Thus in Leagach (Plate LXX) two points reach 3358 feet and 3486 feet; in Beinn Alligin there are also two points reaching 3021 feet and 3232 feet respectively; in Beinn Dearg we have a height of 2995 feet; in Beinn Eighe there are three dominant points, 3188 feet, 3217 feet, and 3309 feet. The four masses to the north are somewhat lower, their elevation being 2860 feet, 2370 feet, and 2892 feet. The mountains of Lochaber and the Monadhliath Mountains exhibit similar relationships; and the same holds good with all the mountain-groups of the Highlands. One can hardly doubt that such relationship is due to the simple fact that the mountains are the remnants of a tableland, the surface of which is indicated approximately by the summits of the several mountain masses. If we in imagination fill up the valleys, we shall in some measure restore the general aspect of the Highland area when the mountains began to be shaped out by Nature's saws and chisels."

It goes without saying that the forms of mountains derived from a plateau of erosion have been determined mainly by the character of the constituent rocks and their geological structure. In the Highlands we are dealing, it will be remembered, with a tableland consisting fundamentally of the relics of a

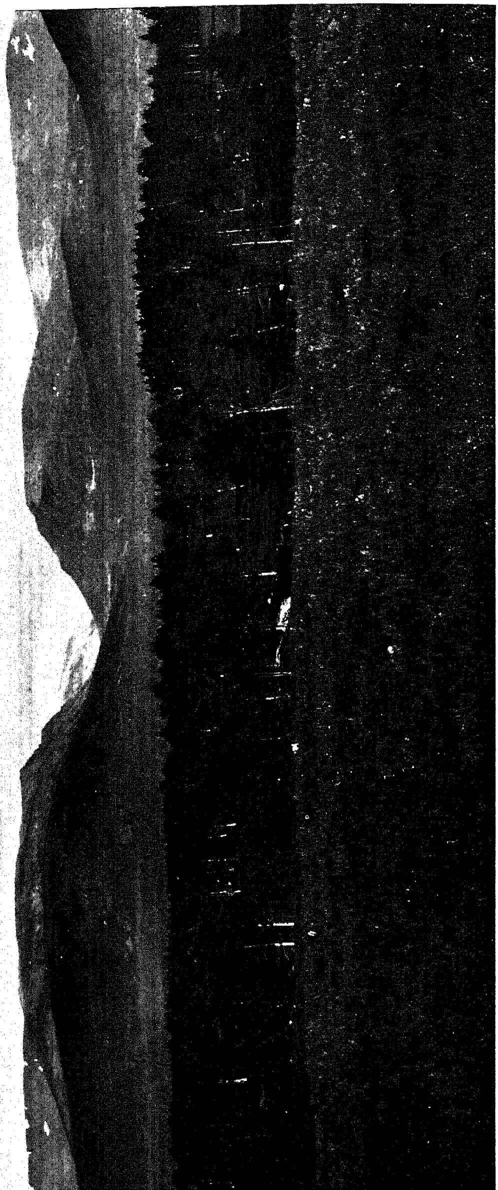
tectonic chain, covered and concealed throughout considerable areas by strata of much later age. The plateau, therefore, so far as its older rock-masses are concerned, has, for the most part, the internal structure of folded mountains. Nowhere throughout the whole region, however, does the configuration of the surface coincide with that structure—anticlinal hills and synclinal valleys are quite unknown. It is remarkable, however, that among the rock-masses constituting the ancient uplifted region, some have retained an approximately horizontal position. This is the case with the Torridonian sandstones which must originally have extended over a very wide area. Considerable portions, however, still remain, forming isolated cone-like or pyramidal mountains, such as Canisp, Soulvein, Stackpolly, and Coulmore, or more closely associated aggregates of similar shaped heights (see Plates LXX, LXXI). The occurrence of this simple type of structure, associated with the travelled rock-sheets and complexly folded rocks of the Highlands, recalls that of the horizontally disposed dolomites of the Alpine lands. There are other tracts of the Highland area where approximately horizontal strata occur, the erosion and denudation of which has resulted in the formation of pyramidal and cone-like heights. But all these relatively undisturbed strata are very much younger than the Torridonian sandstones. The latter were in existence before the uplift of the Caledonides took place, the former rest with a violent unconformity upon the plain of erosion to which these ancient

PLATE LXVIII.

THE HIGHLAND TABLELAND. Mountains of Athol seen from beyond the River Tilt.

Photo, H.M. Geological Survey.

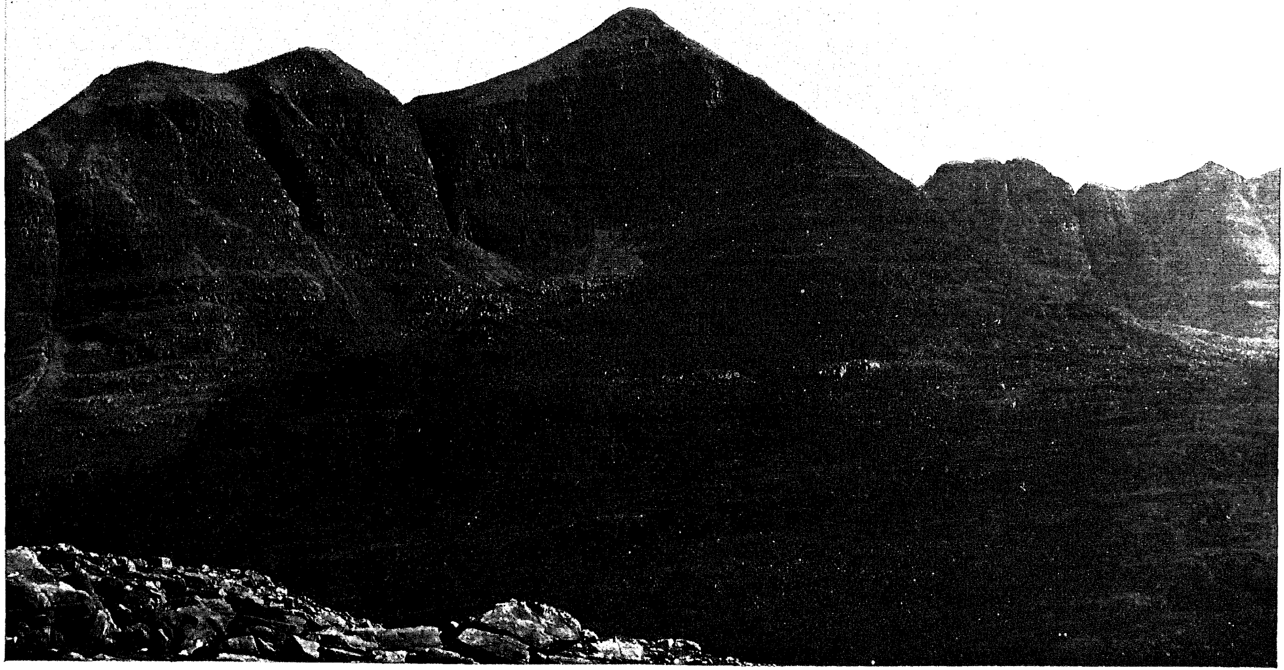
PLATE LXIX.



Plateau of Cairngorm Massif, from Rothiemurchus Forest.

Photo, H.M. Geological Survey.

PLATE LXX.



LEAGACH, WEST ROSS-SHIRE. A mountain of Torridon Sandstone, with a capping of White Quartzite.

Photo, H.M. Geological Survey.

PLATE LXXI.

QUINAIG, FROM NEAR TOMORE, WEST END OF LOCH ASSYNT, SUTHERLAND. Escarpment of Torridon Sandstones which rest upon an irregular platform of Archæan Gneiss (middle distance).

Photo, H.M. Geological Survey.

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mountains had been largely reduced before Old Red Sandstone times. The accompanying section (Fig. 57) across a part of Caithness will serve to illustrate the relation between the Old Red Sandstone and the more ancient rocks.

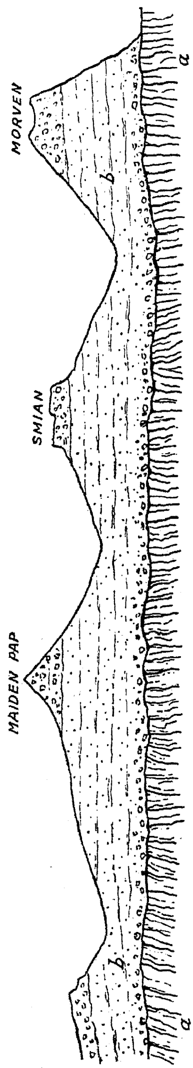

FIG. 57.—Section across Part of Caithness.
a, *a*, Ancient Schistose Rocks; *b*, *b*, Old Red Sandstones.

In Sutherland the mountain masses often assume the form of conspicuous escarpments with dip-slopes. This necessarily arises from the geological structure, the general inclination of the strata being easterly or south-easterly, while the rocks naturally vary in character, some being more resistant than others. In Beinn Arkle, for example, the escarpment represents the outcrop of massive beds of hard quartzite (Cambrian) dipping towards the east, and resting upon an eroded surface of Archæan gneiss (Plate LXXII). Most of the escarpments in the same region, however, have been carved out of what might at first sight appear to be a regular succession of various kinds of rock inclined in the same direction at moderate angles. But the geological structure,

although apparently simple, is in reality very complex, for we are here in the region of great overthrusts, where enormous sheets of Archæan gneiss, Torridonian sandstones, Cambrian strata, and later schistose rocks have been driven upward and forward one over another. In traversing the ground from west to east, therefore, we find the geological succession frequently reversed, older often overlying younger rocks. Many of the escarpments, for instance, are formed of Archæan gneiss, sheets of which come again and again to the surface. Notwithstanding this complicated structure the disposition of the rocks is such that the surface-features due to erosion and denudation do not differ essentially from those attained by a consecutive sequence of alternate hard and less resistant strata inclined in one and the same general direction. It may be remembered that in the Swiss Alps even very highly folded rocks have sometimes yielded to epigene action, much in the same way as horizontal strata—a succession of overlying recumbent folds under denudation, tending to assume the pyramidal and tabular forms characteristic of the latter.

Escarpment-heights are not conspicuous in the central Highlands, although the N.E. and S.W. trend of many of the so-called "ranges" corresponds to the outcrops of certain schistose rocks, the relative hardness of which has doubtless determined the features in question. Apart from such more or less abrupt features, it must be admitted that the general configuration of the mountains is somewhat

monotonous. The rare occurrence of prominent peaks and serrated outlines need not be wondered at, when we bear in mind that the mountains are being slowly developed out of a tableland. As denudation proceeds and the valleys are deepened and widened, the broad mountain-tops will gradually contract to straggling zigzag ridges and strings of peaks. The long sweeping contours of the present will then be replaced by more abrupt and interrupted outlines. In a word, the monotonous plateau features will by and by disappear.

The sameness of the mountain-forms, however, is partly to be accounted for by the fact that the constituent rocks show no great variety of character, schists of one kind or another occupying very wide areas. Now and again the occurrence of limestone, of slates, or of igneous rocks tends to interrupt the uniformity of configuration; but just as frequently they seem to have little influence. The reason is sufficiently obvious. The Highland area has been throughout severely scraped and abraded by glacial action. Only when we get above the limits reached by the old ice-sheets and glaciers does the diversified character of the rocks begin to express itself in greater variety of feature.

It need hardly be said that these remarks on the monotonous features of the Highland area refer only to the mountain-tops. In the valleys and glens where the rocks are laid bare, the scenery is frequently the reverse of tame. The schistose rocks especially often present peculiarly harsh and rugged features, well

seen in Fannich Forest (Ross-shire) and many other districts. In Plate LXXIII, for instance, the schists form gaunt forbidding precipices, often barred by conspicuous ledges—the outcrops of more resistant rocks—and gashed everywhere by vertical fissures and gullies, opened along planes of jointing and crushing. The contrast between the smooth and undulating mountain-tops and the wild aspect of these cliffs is sufficiently striking. The same contrast between rounded hill-top and rugged broken cliff is well illustrated in Plate LXXIV. It need hardly be said that the boldest and steepest cliffs and precipices are developed along the outcrops of the strata, so that now and then we encounter rough escarpment mountains with more or less conspicuous dip-slopes (see Plate LXXV).

Even in those parts of the Highlands where the ancient schists and granitoid rocks are largely concealed under thick sheets of relatively undisturbed rocks of Old Red Sandstone age, many of the glens exhibit similar wild scenery. More especially is this the case when the overlying strata consist of volcanic rocks. Striking examples are seen in Glencoe, where the volcanic rocks are well exposed. Aonach Dubh, for instance, which overlooks the glen from the south, is composed of a series of lavas and associated agglomerates, resting upon a base of schists and granite. The mountain-front rises as a bold escarpment to a height of more than 2800 feet, the rugged character of which is well shown in Plate LXXVI. In Buchaille Etive Mòr the same volcanic rocks

PLATE LXXII.

BEINN ARKLE, SUTHERLAND, FROM THE SOUTH-WEST. [Cambrian Quartzite lying on eroded platform of Archæan Gneiss.]

Photo, H.M. Geological Survey.

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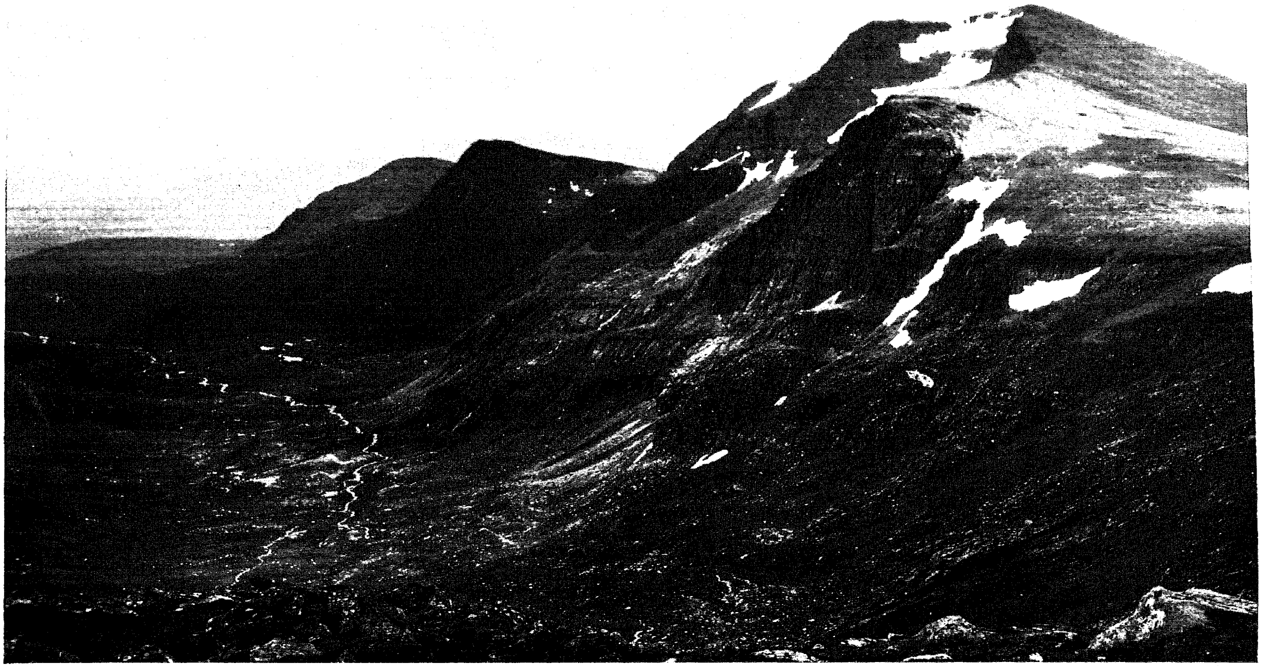

SGÙRR NAN CLACH GEALA, FANNICH FOREST, ROSS-SHIRE.

[Flaggy siliceous schists form lower part of mountain, and gneiss the upper part; the valley on the left strewn with moraines.]

Photo, H.M. Geological Survey.

appear, resting in like manner upon an ancient plane of erosion. The northern peak of this mountain-mass—Stob Dearg—exhibits the same phenomena as Aonach Dubh. The volcanic rocks, constituting the upper half of the mountain, are approximately horizontal, and have consequently assumed the typical pyramidal form (see Plate LXXVII). On the other side of the River Etive rises a group of mountains (Plate LXXVIII) similarly constructed but of less rugged aspect. Their subdued and rounded features, however, are readily accounted for by glaciation; the harsher outlines they doubtless presented in preglacial times have been smoothed off and largely obliterated.

All over the Highlands, indeed, the configuration of mountain-tops and slopes has been modified by glacial action, the softened contours being most conspicuous, of course, when viewed in the direction followed by the old ice-streams. A long time, however, has elapsed since the Ice age, and the flowing monotonous features due to glaciation are gradually disappearing. Nevertheless, even when the finer work, the smoothing and striation, done by the glaciers can hardly be traced, the effect produced by their grinding action may still be seen in the generally abraded aspect of the mountains. It is not often that the shoulders of any Highland mountain fail to show more or less notable evidence of the kind. Note, for example, the rounded aspect of Meall Cumhann, as shown in Plate LXXIX. The fine striation has vanished, but the strongly fluted un-

dulating surface is obviously the result of glacial grinding.

The erosion plateau of the Southern Uplands shows even less diversity than that of the Highlands. The mountains as a rule are broad and flat atop; so much so that when standing on a summit level towards the centre of the Uplands, we seem to be surrounded on all sides by an interminable moorland, extending with a gently undulating surface to the distant horizon. Nevertheless, tame as those heights appear, all have the structure of folded mountains. Great overthrust faults on the scale of those met with in Sutherland do not occur; the dominant structures are vast successions of isoclinal folds. As already indicated the Southern Uplands have much the same tale to tell as the Highlands. Buckled up in Palæozoic times, and forming part of the great uplift of the Caledonides, they were subjected, contemporaneously with the Highland area, to denudation through long ages, and largely base-levelled. Subsequently subsiding, the base-levelled tracts were overspread with Old Red Sandstone and Carboniferous strata, and later on elevation supervened, and the whole region bulged upward as a plateau, a plateau which resembled that of the Highlands in being partly one of erosion and partly one of accumulation. So long a time has elapsed since the tableland of the Southern Uplands appeared, that the later Palæozoic strata which originally overspread much of the base-levelled Caledonides have been to a large extent removed. Looked at broadly,

PLATE LXXIV.

VIEW OF THE CREST OF FANNICH MOUNTAINS, ROSS-SHIRE. [Corries, rugged cliffs, and rounded hill-tops; frost-riven debris arranged in terraces (foreground to right); Loch Fannich in middle distance to right.]

Photo, H.M. Geological Survey.

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therefore, the Southern Uplands resemble the Highlands in general structure. In both regions we can descry an ancient plain of erosion, covered throughout wide tracts by strata which in many places still remain approximately horizontal.[1]

Throughout the erosion plateau of the Southern Uplands the prevalent rocks are greywackés and shales. There is thus much less variety than we encounter in the Highlands. Glaciation also has been just as effective as in the latter. It is not surprising, therefore, that the configuration of the Southern Uplands should be even more monotonous than that of the Highlands. Owing to the larger variety of the rocks and rock-structures of the Highlands, their multitudinous glens exhibit a diversity of feature which we look for in vain among the smooth dales and "hopes" of the Southern Uplands.

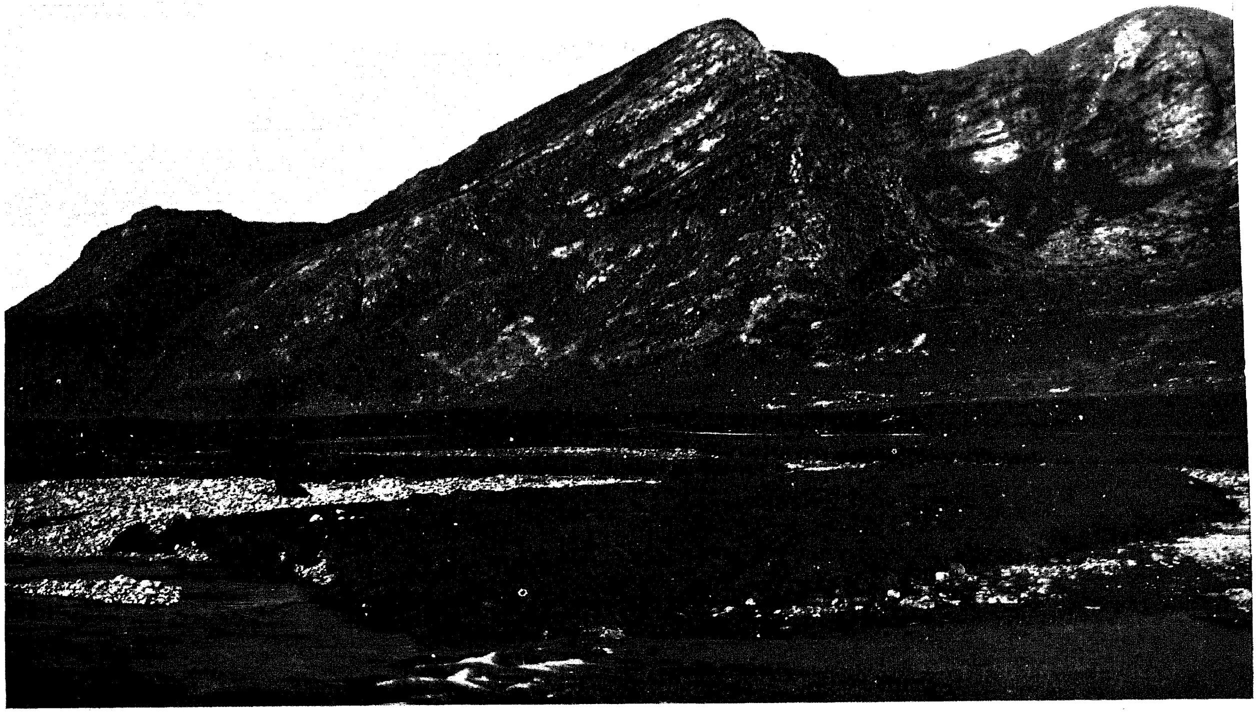
[1] The uplifting of the Southern Uplands dates back to the close of the Silurian period. Before and during Old Red Sandstone times, the land suffered extensive erosion, for deposits of that age rest discordantly throughout wide areas on the upturned edges of the older Palæozoic strata. Partially depressed during the Carboniferous period, it was again uplifted, and experienced renewed erosion and denudation. At what particular date the chief drainage lines of the region were initiated it is hard to say. Possibly they were determined before Permian times; but, as denudation and erosion continued, not only would the earliest formed valleys be widened and deepened, but numerous younger valleys would be successively outlined during later ages. The fact that dykes of basalt, believed to be of Tertiary age, cross certain valleys would seem to show that the latter must either have originated or been greatly deepened since Tertiary times. Evidence of this kind leads to the conclusion that the whole surface of the country—in Highlands, Southern Uplands, and Lowlands alike—has been greatly lowered within the geologically short period that separates the present from the heyday of Tertiary volcanic activity.

Only now and again where they penetrate the higher levels of the erosion plateau do the latter assume a wilder character. The more elevated tracts of Galloway are indeed the only regions in the south of Scotland that can vie in rugged grandeur with the Highlands.

The accompanying sketch sections across the Southern Uplands may suffice to illustrate the general geological structure, and to show how all the surface features are the result of denudation (see Plate LXXX).

Many other elevated tracts lying north of the Pyrenees, Alps, and Carpathians might be cited as monuments of erosion — carved like the Scottish mountains out of erosion plateaus. The mountains of the Lake Country, of Wales, of Ireland are all mountains of circumdenudation, and the same holds true of the Scandinavian heights. Indeed, there is hardly any region under the sun wherein true relict or subsequent hills or mountains do not occur. If we except the great ranges and chains of relatively late origin, such as those that surround the Pacific basin, the Tertiary uplifts of the Himalaya, of the Mediterranean region, etc., as well as every tract of active or recently extinct volcanoes, there are probably few of the remaining elevations of the land of any importance which might not be classed as relict or subsequent. The larger number are monuments of erosion and denudation.

From what has already been said, however, as to the amount of waste which even the youngest



AN COILEACHAN (3015 FEET), FANNICH FOREST, ROSS-SHIRE. [Mountain composed of flaggy schists : showing Escarpment and Dip-slope.]

Photo, H.M. Geological Survey.

AONACH DUBH, GLENCOE, ARGYLESHIRE. [Volcanic rocks of Old Red Sandstone age lying unconformably on schistose rocks.]

Photo, H.M. Geological Survey.

[*Between pages* 280 *and* 281.

accumulation and deformation mountains have experienced, it will be readily understood that it is not always easy to distinguish between these and mountains that are truly relict. The architecture or build of the mountains is often of itself insufficient to decide the question. The remnants of an erosion plateau, for instance, may exhibit all the structures characteristic of highly worn and denuded folded mountains. Not until we have ascertained their geological history, therefore, can we decide as to the character of mountains. If it can be shown, as in the case of the Alps, that a region of uplift has not yet passed through a cycle of erosion, then that uplift must be termed tectonic, no matter what amount of denudation it may have experienced. It is doubtful, however, whether any region of uplift has ever passed through a complete cycle of erosion. Before a mountain chain has been entirely reduced, it may be submerged to a less or greater extent, and become wholly or very largely buried under new accumulations. This, as we know, has frequently been the case. When re-elevation supervenes, the area seems usually to have appeared as a plain or a plateau, dominated perhaps by the still more or less prominent trunks or torsos of the old mountains; but inasmuch as these have passed through a cycle of erosion, they are now properly termed relict, the period of subsidence having as it were closed the tectonic stage of their history.

In preceding chapters we have made frequent reference to the decay of tectonic mountains, and have now and again traced the various stages in the

history of such mountains, without pausing to explain how in course of time they may have lost their original character and become relict. In our account of volcanoes, for instance, we showed how a cone is gradually or more rapidly reduced according to circumstances, until at last all that remains to mark its site may be a plug of rock choking up the old chimney or focus of eruption. As typical examples of such extreme denudation the Scottish "necks" were briefly described. These hills, however, are now truly relict, although similar hills met with elsewhere are properly classed as tectonic. Among the latter we must include the Tertiary "necks" of North America which, however sorely reduced, have never been submerged and covered up by younger formations. The process of demolition in their case has not been interrupted. Quite otherwise has it been with the Scottish examples, most of which had suffered extreme erosion long before the close of Palæozoic times, and eventually subsided and were overwhelmed by vast accumulations of sediment. Since the re-elevation of the Scottish area protracted periods of denudation have supervened, and the strata under which for long ages they lay concealed have gradually been removed. To-day, owing to the superior durability of their materials, they dominate the less resistant rocks with which they are associated, and have thus come to form conspicuous features in our Lowlands. They are no longer tectonic, however, but relict.

In like manner our short sketch of the laccolith

PLATE LXXVII.

Stob Dearg (3345 feet), the Northern Peak of Buchaille Etive Mòr, from the East, Argyleshire.
[Volcanic rocks of Old Red Sandstone age lying on schistose rocks.]
Photo, H.M. Geological Survey.

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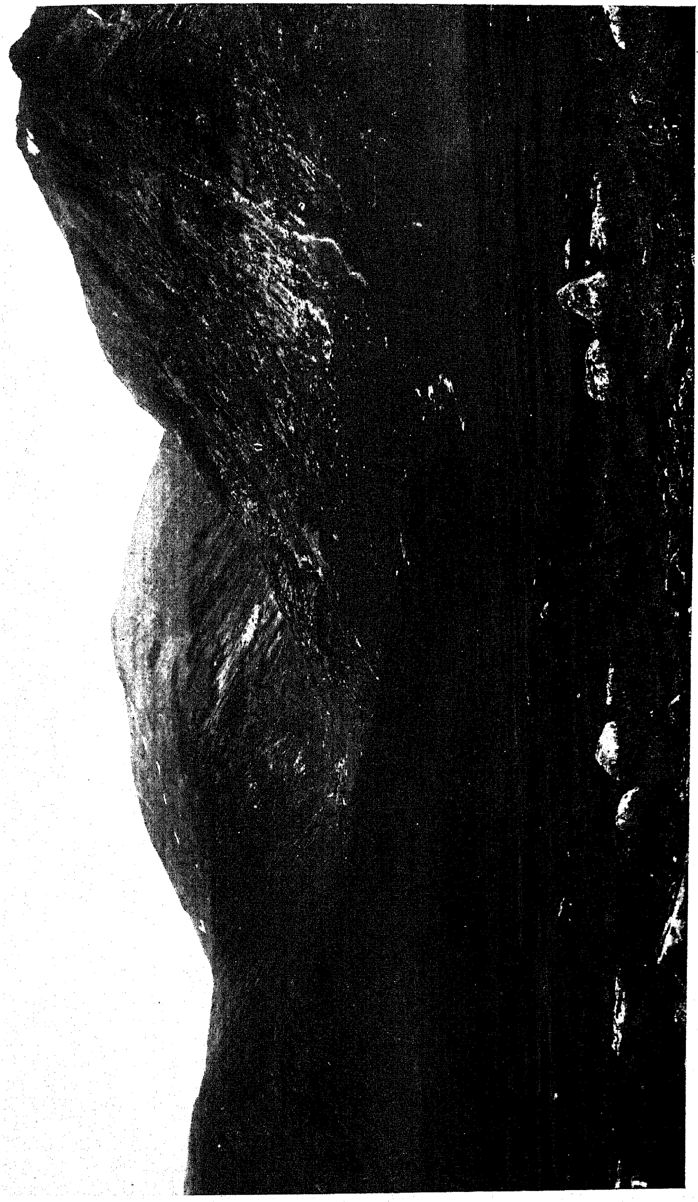
mountains of North America—eminently characteristic tectonic structures—was followed by some account of analogous structures met with in Britain, which, notwithstanding their similarity to the American type, must nevertheless be classed as relict. Their present appearance, like that of the "necks" of Scotland, is due to denudation, for it can be shown that they were formerly buried under a great thickness of sedimentary strata. Their prominence in a landscape, therefore, they owe to their resistant character. Our batholith mountains also are obviously relict, and any description of them ought properly to have been reserved for this concluding chapter. But, having discussed the subject of laccolitic intrusions, and indicated their close relationship to batholiths, it seemed well to consider the latter at the same time.

Again, in treating of dislocation mountains, those of most recent age were necessarily cited first, since they undoubtedly belong to the tectonic class. But we could not avoid referring to others of much greater antiquity which are, nevertheless, rather relict than tectonic. It would have been inconvenient, and would certainly have entailed some repetition and caused confusion, had we deferred all mention of the latter until we came to discuss the origin of relict mountains in general.

In the cases just referred to the distinction we have drawn between Original or Tectonic and Subsequent or Relict mountains may appear to be somewhat arbitrary and even artificial. But although Nature does not often allow of hard and fast lines

being drawn, yet for purposes of description and classification it is not always easy or even possible to avoid pigeon-holing her phenomena. Typical examples of the two great classes of mountains are of course readily differentiated; but, as we have admitted, it is often very hard indeed to say whether a highly worn and denuded mountain is original or subsequent. In the present state of our knowledge it would be impossible to catalogue all the hills and mountains of the world, and assign each to one or other of the two classes. In a multitude of cases, no doubt, there would be little difficulty in doing so; but the geological history of very many others is too imperfectly known to allow of any such attempt. Nevertheless, we know that in course of time mountains, originally tectonic, have eventually passed over into the relict stage; and the line we have attempted to draw between the two stages is not, after all, so arbitrary as it may seem to be. For it is certain that the submergence of much reduced tectonic mountains, whether complete or only partial, marks a definite stage in their history. It is true that some of the old stumps or torsos may never have been completely drowned. They might have peered as islets above the surrounding sea, and when re-elevation supervened they may then, as subdued heights, have overlooked a broad plain or plateau of accumulation. From this point of view, therefore, it seems hard to deny them the title of tectonic or original. But in not a few cases such torso-heights, however naked now, would seem to have been formerly covered with younger

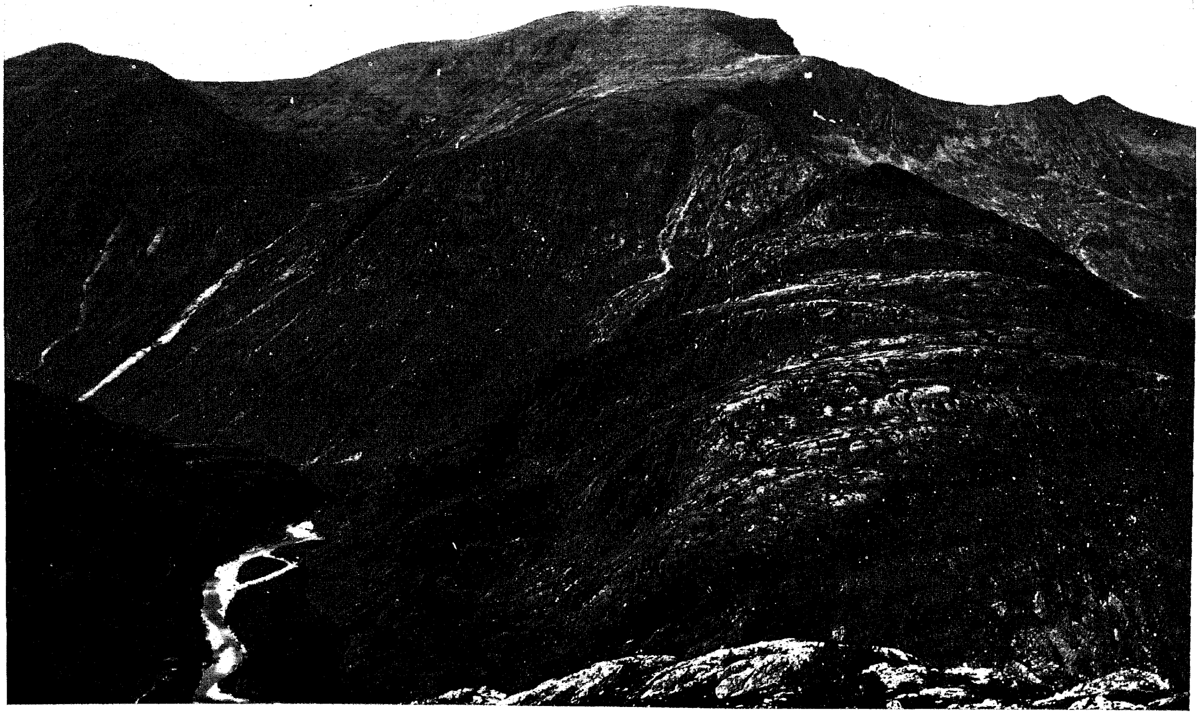
PLATE LXXVIII.



SRON CREISE (2952 FEET) ON THE RIGHT, AND MEALL A' BHURIDH (3636 FEET) IN CENTRE, NEAR KINGHOUSE, ARGYLESHIRE.
[Mountains composed essentially of volcanic rocks of Old Red Sandstone age lying upon Gneiss.]
Photo, H.M. Geological Survey.

[*To face page* 284.

PLATE LXXIX.



BEN NEVIS (4406 FEET), FROM THE SOUTH: MEALL CUMHANN, MIDDLE DISTANCE, ON THE RIGHT.

Photo, H.M. Geological Survey.

formations, showing that their submergence had really been complete. Re-exposed torsos of the kind have obviously lost their tectonic character, and entered on the final or relict stage of their history.

As it may possibly be of convenience to the reader, the classification of mountains followed in these pages is here presented in a tabular form :—

ORIGINAL OR TECTONIC MOUNTAINS.

Accumulation Mountains.

VOLCANIC TYPES

Debris Cones.

Lava Cones.

Cones of Viscous Lava.

Cones of Liquid Lava.

Composite Cones.

Geyser Cones.

Air Volcanoes (pseudo-volcanic).

EPIGENE TYPES.

Glacial Hills.

Æolian Hills.

Deformation Mountains.

Folded Mountains.

Dislocation Mountains.

Laccolith Mountains.

SUBSEQUENT OR RELICT MOUNTAINS.

APPENDIX

I

TABLE OF GEOLOGICAL SYSTEMS

Quaternary or Post-Tertiary . .	Recent. Pleistocene.
Tertiary or Cainozoic .	Pliocene. Miocene. Oligocene. Eocene.
Secondary or Mesozoic .	Cretaceous. Jurassic. Triassic.
Primary or Palæozoic .	Permian. Carboniferous. Devonian and Old Red Sandstone. Silurian, Upper. ,, Lower = Ordovician. Cambrian.
	Pre-Cambrian.
	Archæan.

II

GLOSSARY

Æolian. Applied to derivative formations, the materials of which have been accumulated by wind.

Agglomerate. Volcanic fragmental rock—an aggregate of angular, subangular, and roughly-rounded blocks and smaller stones, showing little or no trace of stratiform arrangement.

Air Volcanoes. See MACALUBAS.

Anticline (Gr. *anti*, against + *klinein*, to lean). A geological structure in which strata dip in opposite directions from a common axis or axial plane. An anticline is *symmetrical* when the axial plane is vertical, and *asymmetrical* when that plane is inclined.

Archæan. See TABLE OF GEOLOGICAL SYSTEMS.

Arenaceous. Applied to rocks consisting largely or exclusively of sand.

Arête (Fr.). An acute rugged mountain-crest or ridge.

Argillaceous. Applied to rocks composed chiefly of clay.

Ashes. The powdery materials of volcanic eruptions.

Autochthonous (Gr. *autos*, self + *chthon*, earth, land). Applied to rocks occurring *in situ:* rocks which have not been displaced from their original position: opposed to exotic (*q.v.*).

Basalt. A dark, hemicrystalline, basic igneous rock.

Base-level. That level to which a land-surface tends to be reduced by denudation (*q.v.*).

Basin. A tract of strata that dip towards a common centre; also the drainage area of a large river and its tributaries; generally

any hollow or depression of the surface, whether occupied by water or not; an area having no outlet is termed a *closed* basin.

Batholith (Gr. *bathos*, depth + *lithos*, stone). An extensive, amorphous mass of intrusive igneous rock which has consolidated at a considerable depth in the crust; now exposed at the surface by denudation.

Blätter (Ger.). Transverse thrusts or transcurrent faults (*q.v.*) occurring in the Alps.

Block Mountain. See HORST.

Blocks. The larger rock-fragments of volcanic eruptions.

Bombs. Clots of molten lava shot into the air during volcanic eruptions: having a rotatory motion they often acquire rudely spherical or elliptical forms, and are frequently vesicular internally or hollow.

Boss. Another term for Batholith (*q.v.*).

Boulder-clay or **Till.** The bottom- or ground-moraine of glaciers and ice-sheets; typically an unstratified clay more or less abundantly charged with angular and subangular stones of all shapes and sizes, many of which are smoothed and striated.

Breccia (It.). A rock composed of angular fragments. Many kinds occur, as *volcanic b.* (composed of volcanic ejecta); *scree-b.* (see SCREE); *cataclastic b.* (due to the mechanical crushing of rocks during movements of the crust).

Bündnerschiefer (Ger.). A series of dark, calcareous and arenaceous shales of Jurassic and Lower Cretaceous age, occurring in the Prättigau and elsewhere in the Alps; they are analogous in petrographical character to the Flysch (*q.v.*).

Buttes (Fr.), and **Mesas** (Sp.). Conspicuous and more or less isolated hills and mountains in the territories of the U.S. America. Buttes are usually craggy, precipitous, turret-like, and irregular in form; Mesas are flat-topped or tabular.

Cainozoic (Gr. *kainos*, recent + *zoe*, life). See TABLE OF GEOLOGICAL SYSTEMS.

Caldera (Sp., a cauldron). A very large crater, the result of a paroxysmal eruption during which the volcanic cone has been

truncated—the upper part of the cone having either been blown away in fragments or engulfed.

Cambrian (*Cambria*, Wales). See Table of Geological Systems.

Cinders or **Scoriæ.** Fragments of cellular spongiform lava ejected by volcanoes.

Circumdenudation Mountains. Another term for relict or subsequent mountains.

Clastic (Gr. *klastos*, broken). Applied to rocks composed of fragmental materials, such as breccia, conglomerate, sandstone, tuff, etc.

Cleavage, Slaty. A structure superinduced in rocks, more especially in argillaceous rocks, by crustal compression, which (as in clay-slate) allows of their being cleaved or split into plates or slabs in a direction independent of the planes of deposition.

Clinkers (Dut. *klinker*, that which sounds). The cinder-like masses forming the crust of some kinds of lava.

Cone-in-cone. The structure seen in many volcanoes when one or more younger cones have grown up within the caldera (*q.v.*) of an older decapitated cone.

Coulée (Fr., flowing). A stream of lava whether flowing or become solid.

Crag-and-tail. A hill or crag presenting an abrupt and often precipitous face on one side, and declining gradually to the low ground in the opposite direction; a structure characteristic of glaciated regions; not infrequently a basin or hollow occurs immediately in front of the crag.

Crust of the Earth. The outer relatively cool portion of the earth which is more or less accessible to investigation.

Curve of Erosion. A typical river has its steep mountain-track, its moderately inclined valley-track, and its very gently-sloping plain-track. In the case of young land-surfaces the change from one track to another is often abrupt; in regions long exposed to denudation such irregularities tend to be more and more reduced—the transition from one track to another becoming increasingly gradual, until eventually a river's course may be represented by a single curve, flattening out as it

descends from its source to the sea. This is the curve of erosion.

Cycle of Erosion. The successive stages in the reduction of a land to its base-level (*q.v.*). A cycle of erosion may be interrupted by a movement of elevation or of depression; in the former case the reduction of the land is delayed, but the action of the denuding agents is increased; in the latter case the land becoming submerged escapes further subaerial erosion, and may eventually be overspread with marine accumulations.

Débâcle (Fr.). A tumultuous rush of water, sweeping forward rock-debris, etc.

Decken. See ROCK-SHEETS.

Deeps. Name given to profound depressions on the floor of an ocean. Those that occur in proximity to the margin of a continent are usually trough-like; those in the central area of an ocean basin are generally more extensive and irregular in form than the coastal or marginal troughs, but not so deep.

Deflation. The denuding and transporting action of wind.

Deformation, Crustal. The flexing and folding, fracturing and displacement of rock-masses; usually attributed to the sinking of the crust caused by the cooling and contraction of the highly-heated interior. Deformations of limited extent are sometimes the result of the uprise and intrusion of molten matter, as in the case of a laccolith (*q.v.*).

Degradation. The wasting or wearing down of the land by epigene action.

Denudation. The exposure of rocks by the removal of overlying materials; the general process of erosion, also the result of that process.

Derivative Rocks. General term for rocks composed of materials derived from the disintegration of pre-existing minerals and rocks by epigene action, and from the debris of plants and animals. Most derivative rocks are of aqueous origin, and are stratified or arranged in beds.

Detritus (Lat., a rubbing away). The materials that result from the breaking up, disintegration, and wearing away of minerals and rocks; as, alluvial deposits generally.

Diorite (Gr. *dioros*, a boundary between). A crystalline igneous rock, belonging to a group intermediate in composition between acid and basic rocks.

Dip. The inclination of strata down into the earth.

Dislocations. See FAULTS.

Dolomite (Dolomieu, a French geologist). A crystalline granular rock composed essentially of bitter spar (double calcium and magnesium carbonate).

Drongs. See ROCK-SHEETS.

Drum, Drumlin (Ir. and Gael. *druim* or *druman*, the back, a ridge). A ridge or bank of boulder-clay alone, or of solid rock and boulder-clay. Two varieties occur—(*a*) long banks, and (*b*) short lenticular hillocks; the former usually consist of glacial accumulations alone: the latter often contain a core of solid rock, or they may show solid rock at one end, and glacial materials at the other.

Dyke. Intrusive igneous rock, which has solidified in a more or less steeply-inclined or vertical fissure, and is therefore wall-like. The term *vein*, or *eruptive vein*, is usually reserved for more irregular and frequently tortuous and branching intrusions.

Ejecta, Ejectamenta. The fragmental materials discharged by a volcano. See ASHES, CINDERS, BLOCKS, BOMBS, LAPILLI.

Eocene (Gr. *eos*, dawn + *kainos*, recent). See TABLE OF GEOLOGICAL SYSTEMS.

Epicontinental (Gr. *epi*, upon + continental). Applied to the relatively shallow seas covering depressed tracts of the continental plateau; as, the North Sea, Okhotsk Sea, Sea of Japan, China Sea, etc.

Epigene (Gr. *epi*, upon + *genes*, produced). Applied to the action of all geological agents of change at or upon the earth's surface: also to all accumulations due to such action.

Erosion. The wearing away of the earth's surface by epigene action.

Erratics. Rock-fragments which have been transported, generally by glaciers or floating ice, and are therefore foreign to the places in which they occur. The term is also applied to the

relics of translated rock-sheets in Switzerland. See ROCK-SHEETS.

Eruptive Rocks. All rocks of igneous origin.

Escarpment. A steep slope having a more or less extensive lateral range, and often terminating upwards in a line of cliffs; generally marks the outcrop of a relatively "hard" bed or group of "hard" beds occurring in a series of "softer" strata, inclined in one and the same direction; the ground in the rear of an escarpment usually falls away at a gentler gradient in the direction of the dip, and is thus termed the *dip-slope.*

Eskers (Ir. *eiscir*, a ridge). Ridges of gravel and sand formed in tunnels at the bottom of the great glaciers and ice-sheets of the Glacial period, when these were in process of dissolution: same as the Swedish *osar.*

Exotic. Applied to the translated rock-sheets of folded mountains: opposed to autochthonous (*q.v.*).

Faults. General term for fractures and displacements or dislocations of the crust. See NORMAL FAULT, OVERTHRUST, REVERSED FAULT, TRANSCURRENT FAULT, THRUST-PLANE.

Fault-escarpment. An escarpment that coincides more or less closely with a line of faulting, the escarpment occurring on the high side of the dislocation.

Fault-scarp. The exposed plane of a fault; usually a normal fault.

Felspathic. Applied to igneous and metamorphic rocks composed largely of *felspar:* also to certain sandstones containing a notable amount of the same mineral.

Flysch. A very thick series of sandstones, marls, and shales of older Cainozoic age—well developed in the Western Alps.

Fluvio-glacial. Applied to the action of water flowing from glaciers and ice-sheets; also to the deposits resulting from that action.

Foliation. The property characteristic of certain rocks which renders them readily divisible into laminæ, plates, or slabs; it is due either to a super-induced cleavage, as in clay-slate, or to schistosity, as in schists. See CLEAVAGE and SCHISTS. The terms foliation and schistosity have much the same meaning,

and are frequently used interchangeably—the former, however, has the wider signification, for it applies to both slates and schists, while the latter applies to schists only. See GRAIN or RIFT.

Formation. A series of rocks having some character in common, whether of origin, age, or composition; often applied to a group of strata characterised by the presence of peculiar or distinctive fossils—a group of subordinate importance to a system (*q.v.*).

Gabbro (It.). A coarsely crystalline basic igneous rock.

Geanticline (Gr. *ge*, the earth + anticline). A bulging or bending up of the crust affecting an extensive region.

Geosyncline (Gr. *ge* + syncline). A great regional depression of the crust. The elongated depressions occurring along the margin of an oceanic basin are sometimes described as *geosynclinal troughs*. See DEEPS.

Gneiss (Ger.). Originally applied to coarsely crystalline rocks having the same mineralogical composition as granite, now generally applied to any very coarse-grained foliated felspathic rock.

Grain or Rift. The direction in which a rock is most readily divided. In sedimentary rocks the grain coincides with planes of deposition; in schists, with planes of foliation; in certain crystalline igneous rocks, as phonolite, with the orientation of some dominant mineral. In many igneous rocks, however, the constituents of which show no definite alignment or orientation, the cause of the "grain" is obscure.

Granite (It. *granito*). A granular crystalline plutonic rock.

Greywacké (Ger. *grauwacké*). An ancient sedimentary rock, often more or less metamorphosed; common in Palæozoic systems.

Ground-moraine. The rock-rubbish formed by the grinding action of glaciers and ice-sheets.

Hade. The inclination of a mineral vein or a fault from the vertical.

Holocrystalline (Gr. *holos*, whole + crystalline). Applied to igneous rocks composed entirely of crystalline ingredients, as granite, gabbro, etc.

Horizon. A deposit belonging to a particular time, and characterised by distinctive features, as by fossils peculiar to itself; a well-marked and readily recognised stage in a geological system.

Horst (Ger.). A hill or mountain bounded by dislocations: a horst or *block mountain* indicates a higher crustal level below which the adjacent low grounds have been depressed.

Hypogene (Gr. *hypo*, under + *genes*, produced). Applied to geological action under the earth's surface, and to the results and products of that action: opposed to epigene (*q.v.*).

Igneous Rocks. Due to the operation of eruptive and volcanic actions. Two great classes are recognised, viz.: *effusive* or *contemporaneous*, and *intrusive* or *subsequent*—the former having been extruded at the surface, and being of the same age as the rocks with which they are interbedded; the latter having been intruded below the surface, and being therefore of later or subsequent origin to the rocks amongst which they have cooled and consolidated. The terms volcanic (*q.v.*) and hypogene (*q.v.*) are nearly synonymous with *effusive* and *intrusive* respectively.

Imbricate Structure. The structure due to reversed faults (*q.v.*) and overthrusts (*q.v.*), which have caused lower or older rocks to overlap higher or younger rocks.

Infraglacial. Applied to deposits formed underneath glaciers and ice-sheets.

Inlier. A mass of rock surrounded on all sides by rocks of later formation.

In situ. In the original situation; applied to minerals, fossils, and rocks which occupy their natural place or position.

Insolation. The geological action of sun-heat upon rocks at the surface.

Intrusive Rocks. See Igneous Rocks.

Inversion. The folding back of strata upon themselves, whereby the order of succession is reversed. See Anticlines, Synclines, Overfold.

Isocline (Gr. *isos*, equal + *klinein*, to lean). Applied to asymmetrical folds, the limbs of which are inclined in one and the same direction.

Joints. Natural division-planes which intersect bedded and amorphous rocks of all kinds. In stratified aqueous rocks two sets of joints usually appear — vertical to the bedding and cutting each other at approximately right angles. In igneous and schistose rocks the joints, as a rule, are less regular; but to this there are exceptions—as in certain granites, gneisses, basalts, etc.—fine-grained igneous rocks now and again exhibiting prismatic jointing or columnar structure.

Jurassic (from *Jura* Mountains). See TABLE OF GEOLOGICAL SYSTEMS.

Kames. Ridges and mounds of sand and gravel generally; now and again they contain or are sprinkled superficially with erratics, while rude rock-rubbish may be associated with them. They are of glacial and fluvio-glacial origin, and would appear to have been accumulated at the terminal margins of large glaciers and ice-sheets.

Klippen (Ger.). Isolated stacks, hills, and mountainous masses resting upon younger formations than themselves; fragments of translated rock-sheets (*q.v.*). The term *drongs* is suggested as an English equivalent of klippen.

Laccolith (Gr. *lakkos*, a cistern + *lithos*, stone). A thick lenticular mass of intrusive igneous rock, which has caused overlying strata to bulge up so as to form a dome-shaped tumescence at the surface.

Lapilli (Lat., little stones). The smaller stones discharged from volcanoes.

Lava (It.). Any igneous rock, whether fluid or solidified, which has flowed out at the surface.

Lee-seite (Ger.). The side of a hill or prominent rock in a glaciated region which has been protected by its position from the abrading action of the ice-flow. The opposite side, exposed to that action and therefore glaciated, is termed the Stoss-seite.

Lithosphere (Gr. *lithos*, stone + sphere). The crust or solid part of the earth.

Longitudinal Valley. A valley which coincides in direction with the strike or general outcrop of the strata; some of these valleys in recent mountains of uplift are synclinal hollows.

Maars. Name given in the Eifel to crater-lakes.

Macalubas. Mud volcanoes, so-called from the Macalube, near Girgenti, in Sicily; also termed *air volcanoes*, *salses*.

Magma. The fluid or molten material which, when cooled and solidified, forms crystalline, hemicrystalline, and glassy rocks.

Massif (Fr.). A principal mountain-mass or an aggregate of mountains.

Mer de Glace. A well-known glacier of the Mont Blanc massif: applied generally to any of the large glaciers or ice-sheets of the Glacial period.

Mesas. See BUTTES.

Mesozoic (Gr. *mesos*, in the middle + *zoe*, life). See TABLE OF GEOLOGICAL SYSTEMS.

Metamorphic (Gr. *meta*, expressing change + *morphe*, form). Applied to rocks which have been more or less completely changed in texture, structure, and mineralogical constitution.

Molasse. Term applied by Swiss geologists to certain Cainozoic formations abundantly developed at the base of the Alps: these deposits belong partly to the Oligocene, but are mainly of Miocene age: they include the Nagelfluh conglomerates of the Rigi, Rossberg, etc.

Monocline (Gr. *monos*, single + *klinein*, to lean). The simplest kind of fold; an abrupt increase of dip in gently-inclined or approximately horizontal strata, followed by an equally abrupt return to the original position.

Monogenetic (Gr. *monos*, single + *genes*, produced). Applied to folded mountains, the result of one movement of crustal compression.

Moulin (Fr., a mill). An approximately vertical cavity or shaft worked out in a glacier by water descending from the surface through a crevasse.

Nagelfluh (Ger.). Name given to the Tertiary conglomerates, etc., of the "Alpine lands." They are strongly developed along the base of the Alps in Switzerland, constituting such well-known mountains as the Rigi, the Rossberg, etc. See MOLASSE.

Neck. A plugged-up volcanic pipe: the throat of an extinct volcano which has been laid bare by denudation.

Névé (Fr.). Granular snow; the condition assumed by snow on its passage into glacier ice.

Normal Fault. A dislocation, the plane of which is inclined in the direction of downthrow.

Nunatak (Eskimo: plural Nunatakkr). A hill, knob, or ridge of rock protruding through the inland ice of Greenland.

Oligocene (Gr. *oligos*, little + *kainos*, recent). See TABLE OF GEOLOGICAL SYSTEMS.

Os, pl. Osar (Sw., ås, åsar). See ESKERS.

Outlier. A detached or isolated mass of rock resting upon and surrounded by rocks older than itself: it occupies its original position, and is simply the remnant of a formerly more extensive formation: not to be confounded with *klippen* or drongs, which are also detached rock-masses, isolated by denudation, but they are not *in situ*, i.e., they do not occupy their original position. See ROCK-SHEETS

Overfold. An overturned or inverted fold; the axis or axial plane so inclined that one limb of the fold is doubled under the other. When the axial plane becomes horizontal, or nearly so, the fold is *recumbent.*

Overthrust. A dislocated overfold; the fold has been ruptured and one limb pushed over the other along a thrust-plane (*q.v.*).

Palæozoic (Gr. *palaios*, ancient + *zoe*, life). See TABLE OF GEOLOGICAL SYSTEMS.

Paysage Morainique (Fr.). Term applied to a region in which moraines (especially terminal moraines) are abundantly developed.

Permian (Perm, a Russian province). See TABLE OF GEOLOGICAL SYSTEMS.

Pleistocene (Gr. *pleistos*, most + *kainos*, recent). See TABLE OF GEOLOGICAL SYSTEMS.

Pliocene (Gr. *pleion*, more + *kainos*, recent). See TABLE OF GEOLOGICAL SYSTEMS.

Plutonic. Applied to deep-seated igneous action; also to igneous rocks which have consolidated at considerable depths from the surface.

Polygenetic (Gr. *polus*, many + *genes*, produced). Applied to folded mountains which are the result of two or more movements of compression.

Pre-Cambrian. See TABLE OF GEOLOGICAL SYSTEMS.

Protogene (Gr. *protos*, first + *genes*, produced). A kind of granite, rendered more or less foliated by compression or crushing.

Pumice (Lat. *pumex*). Any froth-like, foam-like, spongy, porous, or vesicular lava.

Puy (Fr., a hill). Name given in Auvergne to certain extinct volcanoes: applied generally by geologists to volcanoes of inconsiderable dimensions, many of which are the products of only one or two eruptions.

Quadersandstein. Name given in Saxony, Bohemia, and Silesia to the Cretaceous system, from the character of the sandstone of which it is chiefly composed. This rock is traversed by abundant, well-defined, vertical joints, which cause it to weather into square, tabular, and pyramidal hills and pillar-like masses.

Quaternary. See TABLE OF GEOLOGICAL SYSTEMS.

Quartz (Ger.). Common form of silica; the most abundant and widely distributed of all rock-forming minerals.

Quartz-porphyry. A hemicrystalline igneous rock, in which phenocrysts or conspicuous crystals of quartz are often plentiful.

Recumbent Folds. See OVERFOLD.

Reversed Fault. A dislocation, the plane of which is inclined in the direction of upthrow, so that lower rocks on one side have been thrust over higher rocks on the other.

Rift. See GRAIN.

Roches moutonnées (Fr.). Rounded knobs, knolls, bosses, and hummocks of rock: name given to rocks abraded, striated, and smoothed by glacial action. See LEE-SEITE.

Rock-sheets or "**Decken.**" Sheet-like masses of rock, often of great extent and thickness, which during crustal movements have been driven up gentle inclines or over approximately horizontal planes, sometimes for distances of many miles. They seem occasionally to have originated as much flattened overfolds (*q.v.*), the middle limb in each case having given way to tangential compression, and been replaced by a thrust-plane (*q.v.*). Often, however, rock-masses subjected to such excessive compression have yielded without any preliminary folding, and vast slices have been forced successively for miles one over another. The structures are more or less characteristic of folded mountains.

Roots. Name given to the basal portions of the great asymmetrical synclines (*q.v.*) or downward folds of strata, as displayed in the Alps and similar mountains.

Saddleback. See ANTICLINE.

Salses. Another name for Macalubas (*q.v.*).

Schist (Gr. *schistos*, divisible). Any metamorphic crystalline rock, the constituent minerals of which are arranged in closely parallel lenticular layers or folia; hence the rock is more or less readily divisible along these planes of foliation.

Scoriæ. See CINDERS.

Screes (Icel. *skritha*, fallen rocks on a hillside). A Westmoreland term for sheets of loose stones which gather upon hillsides, and at the base of cliffs, etc.

Shearing. The yielding of a rock to compression, strain, and tension during crustal movements, whereby the solid mass is compelled to flow; frequently under such conditions dislocation takes place—the rock gives way, and one mass is pushed over another. See OVERTHRUST, ROCK-SHEETS, THRUST-PLANE.

Sheet. See SILL.

Sill (Lat. *solea*, sill, sole of the foot). A broad sheet of crystalline igneous rock which has been intruded along a more or less definite plane, as between bedded rocks; hence a sill commonly assumes the appearance of a bed or stratum.

Slags. Common term for the coarser scoriæ (*q.v.*) ejected by volcanoes.

Slaty Cleavage. See CLEAVAGE.

Sole-plane. See THRUST-PLANE.

Stoss-seite. See LEE-SEITE.

Strike. A line drawn at right angles to the dip or inclination of strata: the general direction or run of the outcrops of strata.

Syncline (Gr. *syn*, together + *klinein*, to lean). A geological structure in which strata dip in opposite directions towards a common axis or axial plane. A syncline is *symmetrical* when the axial plane is vertical, and *asymmetrical* when that plane is inclined.

Systems. The larger divisions of strata included under the Palæozoic, Mesozoic, Cainozoic, and Quaternary Groups.

Terrigenous. Usually applied to marine deposits, the materials of which have been derived from the land; opposed to abysmal, applied to deep-sea accumulations, the constituents of which have not been so derived.

Tertiary or Cainozoic. See TABLE OF GEOLOGICAL SYSTEMS.

Thrust-plane or Sole-plane. The plane along which a rock-sheet (*q.v.*) has been translated or driven during crustal deformation. See OVERTHRUST, ROCK-SHEETS.

Till. See BOULDER-CLAY.

Tors. The peculiar and often fantastic prominences met with in regions of granite which have been long exposed to weathering, as on Dartmoor. The *kopjes* of Mashonaland are an example of the same phenomenon.

Torso Mountains. The more or less prominent heights that now and again diversify the surface of a plain of erosion; the remnants of an elevated or mountainous region which has been largely denuded to its base-level.

Trachyte (Gr. *trachys*, rough). A hemicrystalline volcanic rock.

Transcurrent Faults or **Transverse Thrusts.** Steeply-inclined or vertical dislocations that traverse strata at right angles to the *strike* (*q.v.*). They are neither upthrows nor downthrows, movement having taken place in a forward direction, so that

the walls of the faults are striated horizontally, one rock-mass having been rubbed or ground against the other, the latter being either passive at the time or moving more slowly than its neighbour. Faults of this kind are restricted to the translated rock-sheet traversed by them; they do not affect the underlying rocks over which the rock-sheet was driven.

Transverse Valley. A valley that crosses the general strike (*q.v.*) of the strata.

Triassic (Gr. *trias*, three). See TABLE OF GEOLOGICAL SYSTEMS.

Troughs. See GEOSYNCLINE, DEEPS.

Tuff. A volcanic fragmental rock; usually consisting of the finer-grained ejecta of volcanic eruptions; may be composed entirely of lapilli (*q.v.*) or of the finest sand or dust, or of a mixture of coarse and fine ingredients.

Unconformable. Not conforming in position, or not having the same inclination or dip as the immediately underlying rocks; applied to strata which rest upon an eroded surface of older rocks; *unconformity*, the condition of not being conformable.

Verrucano (It.). A zone of conglomerates and sandstones, with occasional carbonaceous shales, that occurs on both sides of the Alps, occupying a position between the Trias and the older rocks of the chain. It has been referred in part to the Permian system.

Wâdi (Ar.). A ravine or water-course, dry except in the rainy season. Some wâdis are perennially dry.

INDEX

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